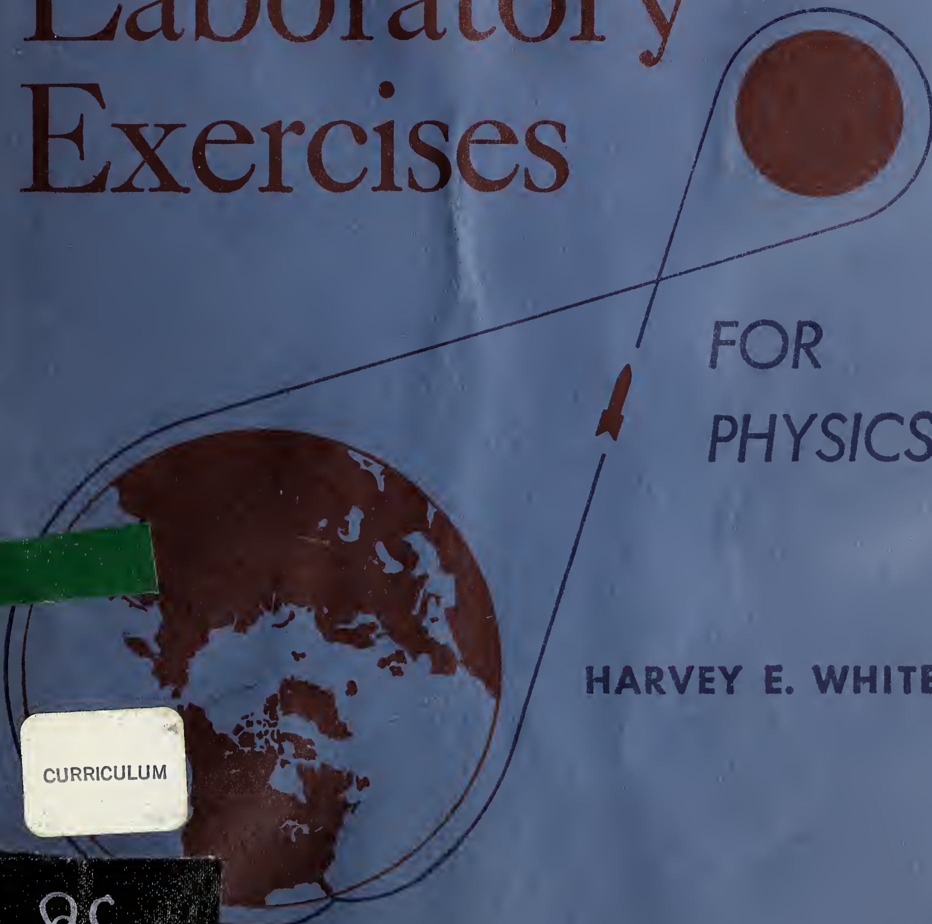
Laboratory Exercises



FOR PHYSICS

HARVEY E. WHITE

LABORATORY EXERCISES for Physics

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Preface

Laboratory Exercises for Physics is designed to be used as a laboratory guide and manual for students enrolled in an introductory course in fundamental physics. Although this manual may be used in conjunction with any well-written textbook, the numbered order of the experiments follows the numbering system used in the author's text, *Physics—An Exact Science*.

It is assumed here, as well as in the associated text, that the student has had some training in the elementary principles of algebra and plane geometry.

For a number of years a large majority of laboratory manuals have been published in an oversized format in which blank spaces are provided for the student to use in recording his own data and in giving answers to specific questions. While this procedure has definite advantages for teachers and students alike, it has also had a number of disadvantages. Recent discussions among teachers clearly indicate that some modifications of procedure should be made.

With the hope of retaining the major advantages of such laboratory practices, and of replacing the objectionable features by more desirable ones, the author is presenting this somewhat new solution to the problem of laboratory procedure.

The scientific method of today is one of experimentation. It is a procedure in which a problem or objective is first outlined and clearly stated by the experimenter. This is followed by a review of the theory and experimental observations of others, and the resulting knowledge, having a direct bearing upon the problem. Apparatus is then constructed and assembled, observations of events are made, and quantitative measurements are recorded in tabular form. Results are calculated according to the indicated theory, and conclusions are usually presented in the form of a graph and one or more statements.

While many schools have excellent laboratory facilities and equipment, others have little or none. As science progresses, new and important experiments must be incorporated into the laboratory experience, and this, of necessity, must be done at the expense of less important experiments previously listed.

Elaborate and expensive equipment for

new and up-to-date experiments need not always be purchased. Through the "project" method, apparatus can often be built by the students and teacher in the home or school workshop. Every school would do well to provide time, space, and shop facilities where talented students can carry out project work. Where a project development is also aimed at Science Fair display and competition, the apparatus should by all means be simple in construction, neat in appearance and operation, and capable of permitting the taking of quantitative measurements.

When laboratory facilities and equipment are available for any of the experiments described in this book, the instructions given should be followed by the student. The sample calculations near the end of each lesson may be used as a student guide in making the calculations necessary to the completion of a "final report."

When laboratory facilities and equipment are not available for an experiment, it is still possible for the student to derive some benefit from the experiment by having him use the data given in the exercises, record them as though they were his own findings, and write a final report based upon these data.

One of the principal criticisms made of many students entering colleges and universities today is their inability to write a composition or report. It is not sufficient therefore that the science student perform each experiment with his own hands; he must also make out his own data sheet, and write up his own final report.

It is recommended that each student's data be recorded in a notebook, and that a clean page be started for each experiment. In this way the original recorded measurements will not be lost, and a periodic check upon any or all of the laboratory work completed can be made at any time.

A sample "Data Sheet" is shown in the appendix along with a brief form of a "Final Report," based on the laboratory experiment in Mechanics on page 6. The sample "Final Report" is not intended to be followed exactly for all experiments, but to serve as a minimum requirement guide for student laboratory and homework. Lengthy reports should not take the place of short, concise, and clearly written ones, but some kind of report written by the student is a very necessary part of science training.

Berkeley, California HARVEY E. WHITE
June, 1959

Contents

Instructions to Students

In performing any of the various laboratory experiments described in the following lessons, you as a physics student should carry out the various steps and procedures outlined as follows. If you have access to apparatus similar to that described in the lesson, by all means do the experiment yourself, record your own data, and write a Final Report. If, on the other hand, you do not have access to laboratory equipment of the kind described, do the next best thing: record the data given in that particular lesson and write a Final Report as if you had performed the experiment yourself. (Oftentimes you may find it a simple matter to procure or make the apparatus yourself.)

If you do perform the experiment, you should record your data on a Data Sheet, following the sample form given on page 173. For this purpose use a sheet of plain white paper, $8\frac{1}{2}$ x 11 in. in size, and record all measurements, diagrams, formulas, and information you think will be needed in writing up your Report. Whether you do the experiment yourself or use the data given in the lesson, your Final Report should be made on the same size paper and have the following brief form (See Sample Final Report on page 175.)

With your Name at the upper left corner of the page and the Title of the experiment at the upper right corner of the page, write down the Object of the experiment.

Following this, and under the heading of Theory, you should give the formulas needed in the experiment. These will generally be copied directly from the book, and they will be connected directly with preceding lessons in the text.

Next, under the heading of Apparatus and Procedure, make a simple line diagram of the apparatus used. Following this, under the heading of Data and Measurements, list your measurements in a well-drawn Table similar to that given in each laboratory exercise.

Next, under the heading of Calculations or Calculated Results, give the numerical calculations asked for. These will often be in tabular form. Finally, under the headings of Results and Conclusions, give the final numerical results obtained, answers to all questions asked, and a graph wherever it is requested.

Neatness is a prime requisite of a good report. Use a ruler in making diagrams and in ruling tables.

INTRODUCTION

MEASUREMENT OF DISTANCES AND ANGLES

In performing the laboratory experiment described in this lesson, you will learn how to measure the three angles of a triangle with a ***protractor*** and the lengths of the three sides with a ***centimeter rule.*** In learning to use these simple measuring instruments, you will learn how to ***interpolate.***

Theory. Suppose that you are going to determine accurately the length of a rectangular block of steel with a centimeter rule. With one end of the block at the zero end of the rule, the other end is found to come a little beyond the 8-cm mark as shown in Fig. A.

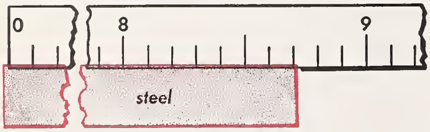
In this illustration you could write down the length as 8.7 cm or 8.8 cm; or you could be more precise and note that the end comes about 4/10 of a millimeter beyond the seventh millimeter mark. Hence you could write more precisely 8.74 cm. This process of making a reasonably good estimate as to an intermediate value is called ***interpolation***. In laboratory practice of all kinds, this process of interpolation arises over and over again, and the more carefully you make your estimates, the more precise you can expect your results to be and the more reliable will be the conclusions you decide to draw from them.

To measure the angle between two lines, a protractor of the kind shown in Fig. B is most commonly used. Protractors usually include angles up to half a circle; therefore, they permit the measuring of angles up to 180°. In the illustration the scale starts at the right and measures angles up and around counterclockwise.

While some precision angle-measuring devices divide each degree of angle into 60 minutes and each minute into 60 seconds, we will always divide them decimally into tenths and hundredths of a degree.

Suppose, for example, the angle θ is to be measured with your protractor. Close examination of the scale in the region of 42° might look like the detail in Fig. C. The

Fig. A. Illustrating the process of interpolation when used in measuring a length.



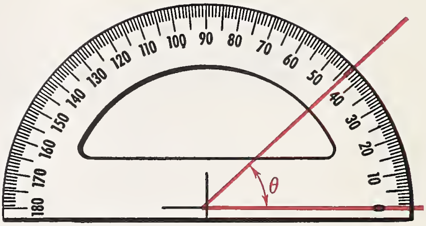


Fig. B. Diagram of a protractor as used in measuring angles.

Fig. C. Illustrating the process of interpolation in measuring angles.

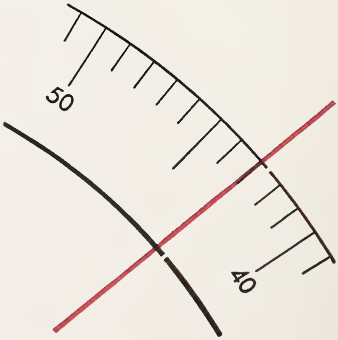


Table 1. Measurements of the Sides and Angles of Two Right Triangles

Trial	AC (cm)	AB (cm)	CB (cm)	Angle A (degrees)	Angle B (degrees)	Angle C (degrees)
1	8.00	9.77	5.60	35.0	55.0	90.0
2	7.50	11.0	8.04	47.0	43.0	90.0

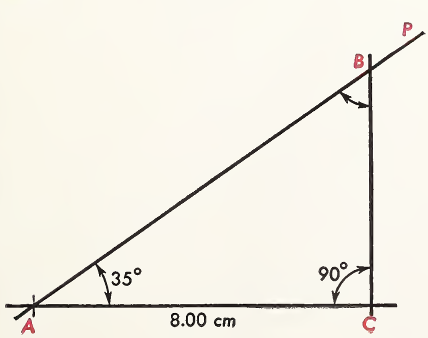
line comes beyond the 42° mark, but not quite to the 43° mark. Interpolating, you could write the angle as 42.6°.

Apparatus. Needed for this experiment are a sharp pencil, a centimeter rule, a protractor, and a sheet of white paper $8\frac{1}{2}$ x 11 in.

Object. To measure the three sides and three angles of a triangle.

Measurements and Data. Draw a horizontal line on your paper and make two marks on the line exactly 8 cm apart, labeling them ***A*** and **C**. See Fig. D. With the center mark of the protractor on ***A***, make a mark at the 35° angle and draw the line ***AP***. With the center mark of the protractor at **C**, make a mark at the 90° angle and draw the line **CB**. Now measure the lengths of the lines ***AB*** and **BC** and record them in a table with column headings like those in Table 1. Also measure

Fig. D. Laboratory exercise in measuring lines and angles.



the angle at ***B*** and record its value. Note that the sum of the angles at ***A*** and ***B*** should be 90°.

As a second trial, repeat the experiment, using a horizontal line 7.5 cm in length and angles ***A*** and **C** of 47° and 90°, respectively. When your measurements are completed and recorded, they will, if carefully done, be close to the values given in Table 1.

If you have time, you may choose different line and angle values for your triangles and record the measurements in Table 1.

Calculations. You may well recall the ***Pythagorean theorem*** from geometry in which it is proved that for all right triangles ***the square of the hypotenuse is equal to the sum of the squares of the other two sides.*** For the triangle in Fig. D, we can therefore write

$$\boxed{(AB)^2 = (AC)^2 + (CB)^2} \qquad (1)$$

We can use this equation as a check upon the accuracy of the measured lengths of the sides of the triangles.

Comparisons are most easily made by tabulating as in Table 2. Note how well the values in the last two columns agree.

Table 2. The Pythagorean Theorem Applied to Two Measured Triangles

Trial	$(CB)^2$	$(AC)^2$	$(AB)^2$	$(AC)^2 + (CB)^2$
1	31.4	64.0	95.5	95.4
2	64.6	56.2	121.0	120.8

Conclusions: Hence we conclude that with a protractor we can measure angles with precision, and with a centimeter rule and the process of interpolation we can accurately measure lengths of lines to three significant figures.

We can apply the Pythagorean theorem to our measured results and with confidence feel that the fundamental principles upon which they are based are valid.

In your report on this experiment, answer the following questions:

1. What is the Pythagorean theorem?
2. What is meant by the term "interpolation"?
3. How many degrees are there in (a) a right angle and (b) a complete circle?
4. The lengths of the two sides of a right triangle are 5 cm and 12 cm, respectively. Find the length of the hypotenuse by means of the Pythagorean theorem.

MECHANICS

SPEED AND VELOCITY

Theory. This is to be a laboratory lesson in which we will see how to determine the speed of an electric train and the velocity of a toy automobile. The principles to be employed are those presented in the preceding lesson, in which the scalar quantity ***speed*** and the vector quantity ***velocity*** are both given by the same algebraic equation

$$\boxed{v = \frac{s}{t}} \qquad (1)$$

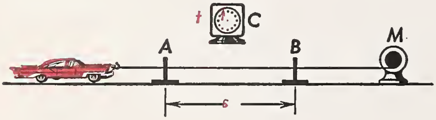
where s is the distance travelled, t is the elapsed time of travel, and v is the speed or velocity.

Apparatus and Procedure. ***Part 1.*** For an object to move with constant velocity, it must not only travel equal distances in equal intervals of times, but its direction must also not change, i.e., it must move along a straight line. For this part of the experiment, a model car is pulled across the table top by means of a string wrapped around a drum, and a stop clock, **C**, is used to measure the time. See Fig. A.

A small synchronous motor ***M***, with a geared down shaft making one revolution per second, and a drum one inch in diameter makes a suitable power unit.

Two markers, ***A*** and ***B***, are located a short distance apart and the distance s between them, is measured with a meter stick and recorded in centimeters. For recording data make a table of three columns as shown in Table 1. The car is started, and as it passes marker ***A***, the clock is started; and as it passes marker ***B***, the clock is stopped. The time t in seconds, as read on the clock dial, is then recorded. This procedure is then repeated with the markers farther and farther apart, and the data are recorded in the table.

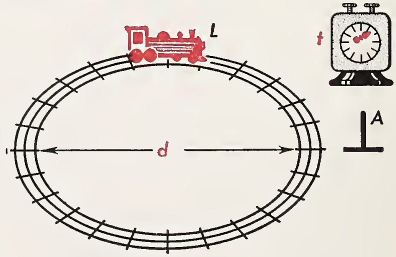
Fig. A. Experimental arrangement for measuring the velocity of a car.



Part 2. For an object to move with constant speed, it may move along any path, straight or curved, but it must travel equal distances along its path in equal intervals of time. For this part of the experiment, a toy electric train is used, running at constant speed around a circular track as shown in Fig. B. Make a table of three columns, with heading as shown in Table 2, for recording data.

As the train passes marker ***M***, the clock is started. The clock is stopped as the train again passes marker ***M***, but after it has made three, four, or five complete trips around the track. The time t is read from the clock directly and the distance is determined by measuring the diameter d of the center rail.

Fig. B. Experimental arrangement for measuring the speed of a train locomotive.



Since the circumference of a circle is given by

$$\text{circumference} = \pi d$$

the total distance s traveled by the train will be

$$s = n\pi d \tag{2}$$

where n is the number of trips around the track, and π has the value

$$\pi = 3.14$$

The distances traveled and their corresponding times of travel should be recorded in Table 2 and the speed calculated by use of Eq. (1)

Object. *To make a study of a body moving with constant speed and another moving with constant velocity.*

Measurements and Data. Suppose that we have performed the experiments just described, made the specified measurements, and recorded the data as they are shown in Table 1.

Table 1. Data for Car

Trial	Distance s (cm)	Time t (sec)
1	72.9	9.1
2	124.5	15.5
3	163.0	20.5

Table 2. Data for Train

Trial	Number of Turns	Time t (sec)
1	3	19.2
2	4	25.5
3	5	32.1

The center rail of the train's circular track is measured and found to have a diameter

$$d = 74.6 \text{ cm}$$

Calculations. To make your calculations of the speed and velocity, use a ruler and construct two new tables having the following headings.

Table 3. Results for the Car

Trial	Distance s (cm)	Time t (sec)	Velocity v (cm/sec)
1	72.9	9.1	8.01

Table 4. Results for the Train

Trial	Number of Turns	Time t (sec)	Distance s (cm)	Speed v (cm/sec)
1	3	19.2	702	36.6

The first three columns of each table are to be filled in for all trials by copying the measured data from Table 1. The remaining columns are then filled in by making the proper calculations: For example, for trial 1 for the car, divide the first distance, $s =$ 72.9 cm, by the time, $t = 9.1$ sec, and you will obtain 8.01 cm/sec. Therefore, as the velocity for the first trial, record in the last column of Table 3 the value 8.01. This has already been done in the case of the first trial and is to serve as your guide in calculating the other two. When similar calculations have been carried out for all three trials, the velocities should be nearly alike.

To find the distances traveled by the train, use Eq. (2). First multiply the measured track diameter $d = 74.6$ cm by $\pi = 3.14$ to obtain the track circumference. Next multiply this circumference by three, four, and five, respectively, and record these in column 4 of your last table. Finally, calculate the train speed by dividing the distances in the fourth column by the measured times in the third column and record the

answers in the fifth column. Again all three speeds should be nearly alike. Calculated values for trial 1 are already given and will serve as your guide for the other two.

Conclusions. For your conclusions, answer each of the following questions:

1. What is the average value of **v** for the car?
2. What is the average value of **v** for the train?
3. Which of the two measurements in this experiment, ***time*** or ***distance***, has the greater percentage error?

Mechanics | **Lesson 4**

ACCELERATED MOTION

Theory. This is a laboratory lesson in which we are going to make a study of a steel ball undergoing uniformly accelerated motion. In the preceding lesson, we have seen the development of four fundamental equations of the form

$$v = at \quad (1)$$

$$s = \frac{v}{2}t \quad (2)$$

$$v^2 = 2as \quad (3)$$

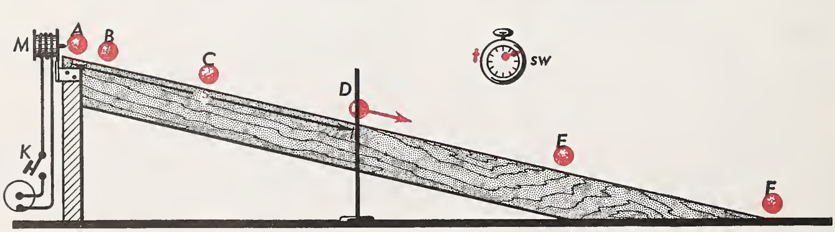
$$s = \tfrac{1}{2}at^2 \quad (4)$$

Note that each of these four equations involves only three of the four quantities, **v**, **a**, **t**, and **s**. In other words, if in any observations of an object moving with uniformly accelerated motion we can measure two of these four quantities, the other two can be computed by using the appropriate equations.

Apparatus and Measurements. There are many methods for producing uniformly accelerated motion and of observing and measuring such motion. In this experiment, we use an inclined plane in the form of a U-shaped metal track down which we roll a steel bearing ball 1 in. in diameter. The apparatus is shown by a diagram in Fig. A.

Part 1. The steel ball is held at the top of the incline by a small electromagnet ***E***. When the electrical switch ***K*** is opened, the magnet loses its force of attraction and the ball is released. As it rolls down the incline, constantly increasing its speed, we propose to measure distances **s** and times of travel **t**. To do this, a marker is set up at any point and the distance **s** is measured

Fig. A. Inclined plane experiment for studying uniformly accelerated motion.



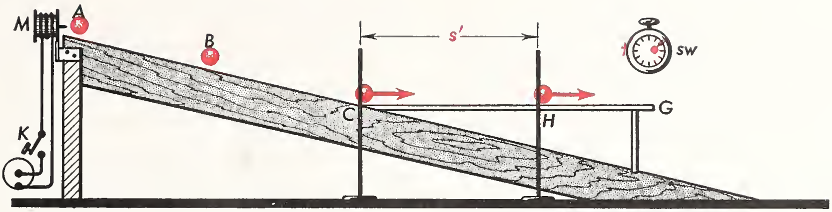


Fig. B. Inclined plane apparatus for measuring instantaneous velocity at any point.

with a meter stick and recorded. At the instant the switch ***K*** is opened, and the ball starts, the stop-watch stem is pressed, starting the second hand from zero. As the ball passes the marker position, the watch stem is again pressed, stopping the watch. Hence ***t***, the time of travel, is determined and recorded. All data in this experiment is conveniently recorded in a table of five columns with headings as shown in Table 1.

Part 2. Although measurements of **s** and ***t*** in this experiment are sufficient to determine velocity ***v*** and acceleration ***a***, we will check the results by measuring the instantaneous velocity of the steel ball as it passes various points along the inclined plane. How this is accomplished is shown in Fig. B.

Suppose, for example, that as the ball rolls down the incline with ever increasing speed, we wish to find its instantaneous velocity as it passes the point **C**. A horizontal track **CG** is mounted on the incline so that the next time the ball rolls down and reaches the point **C** with a given instantaneous velocity ***v***, it will roll out along the level track, maintaining a constant speed ***v***. If we then measure the time ***t′*** required to move a distance **s′** along the level track, we can calculate the velocity ***v*** by the formula

$$v = \frac{s'}{t'} \qquad (5)$$

The procedure, therefore, is to place a marker at **C** and one farther along at some measured distance **s′** as shown in the figure. Upon releasing the ball at ***A***, the stop watch is started as the ball passes the point **C** and stopped as it passes the point ***H***. Hence the distance **s′** and corresponding time ***t′*** can be recorded and ***v*** can be calculated.

Object. ***To study the laws of uniformly accelerated motion.***

Data. Suppose we have performed the experiments just described, made the appropriate measurements, and recorded the data in a table as shown in Table 1.

Table 1. Data for Inclined Plane Experiment

Trial	s (cm)	t (sec)	s′ (cm)	t′ (sec)
1	45.0	1.3	84.0	1.2
2	117	2.1	155	1.4
3	270	3.2	155	0.9

Calculations. To complete this experiment, use a ruler and make two tables of three columns each with headings as shown in Tables 2 and 3.

Table 2. Velocity Results

s'/t' (cm/sec)	$2s/t$ (cm/sec)	Average
70.0	69.2	69.6

To illustrate how the columns are to be filled in, the calculations for the first trial

Table 3. Acceleration Results

v/t (cm/sec^2)	$2s/t^2$ (cm/sec^2)	$v^2/2s$ (cm/sec^2)
53.5	53.2	53.8

are tabulated below each heading. To verify the method, use the following procedure: For the first column headed s'/t' in Table 2, take $s' = 84.0$ cm and $t' = 1.2$ sec from the last two data columns of Table 1, divide one by the other according to Eq. (5), and obtain $v = 70.0$ cm/sec. For the second column headed $2s/t$, take $s = 45.0$ cm and $t = 1.3$ sec from the second and third data columns of Table 1, divide $2s$ by t according to Eq. (2), and obtain $v = 69.2$ cm/sec. These two values of v should be the same. Their average value $v = 69.6$ cm/sec is obtained by adding the two and dividing by 2.

For the first column headed v/t in Table 3, take the average value of $v = 69.6$ cm/sec from Table 2 and $t = 1.3$ sec from data column 3, Table 1, divide one by the other according to Eq. (1), and obtain $a = 53.5$ cm/sec^2. For the second column, take $s = 45.0$ cm and $t = 1.3$ sec from data columns 2 and 3, Table 1, divide $2s/t^2$ according to Eq. (4), and obtain $a = 53.2$ cm/sec. Finally, for the last column, take the average value of $v = 69.6$ cm/sec from Table 2 and $s = 45.0$ cm from the data column 2, Table 1, divide $v^2/2s$ according to Eq. (3), and obtain $a = 53.8$ cm/sec^2. Note how nearly all three of these values of a are alike.

Carry out the procedure just outlined for the other two trial sets of data and tabulate them in the proper columns of Tables 2 and 3. The average values of v for each of the three trials will be different but all nine values of a should be the same.

Results. For your final results, carry out the following:

1. Calculate the average value of the acceleration.
2. Plot a graph of t vs v. Plot t vertically.
3. Plot a graph of t vs s. Plot t vertically.
4. Plot a graph of t^2 vs s. Plot t^2 vertically.

***Mechanics* | Lesson 8**

FALLING BODIES

Theory. In this laboratory experiment, we are going to determine the acceleration due to gravity by measuring the acceleration of a freely falling body. We have seen in Mechanics, Lesson 7, that such bodies, neglecting air friction, should fall with uniformly accelerated motion and that this motion may be described by four kinematic equations of the form

$$v = gt \tag{1}$$

$$s = \frac{v}{2}t \tag{2}$$

$$v^2 = 2gs \tag{3}$$

$$s = \tfrac{1}{2}gt^2 \tag{4}$$

The constant g in these equations is the acceleration due to gravity, and it is our purpose to determine its value with precision. To do this, we will make use of one equation only, Eq. (4). By measuring s, the distance an object is allowed to fall, and t, the time it takes to fall that distance, the values can be substituted in Eq. (4) and g, the only unknown, can be computed. For convenience, transpose Eq. (4) so that g

only is on the left side of the equality sign. Reversing the equation first, write

$$\tfrac{1}{2}gt^2 = s$$

$$\frac{gt^2}{2} = \frac{s}{1}$$

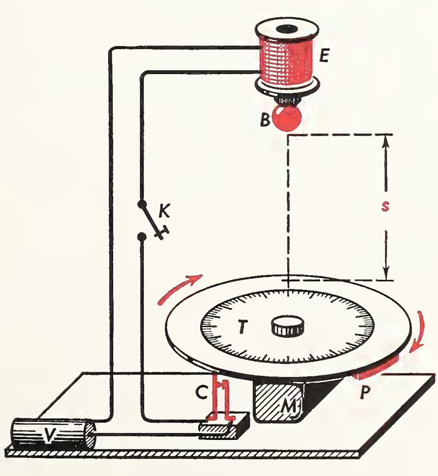
and then transposing, we obtain

$$\boxed{g = \frac{2s}{t^2}} \tag{5}$$

Apparatus and Procedure. The apparatus in this experiment consists of two essential parts: (1) an electromagnet for holding and dropping a steel bearing ball and (2) a turntable driven by a synchronous electric motor for accurately measuring the time of fall. See Fig. A.

The synchronous motor ***M*** keeps in step with the 60-cycle electric current, as does every household electric clock, and is geared down so that the turntable ***T*** makes exactly one revolution per second. The white face of the turntable is divided angularly into one hundred equal divisions as shown in Fig. B. Each division therefore represents $\frac{1}{100}$ of a second.

Fig. A. Apparatus used in determining the acceleration due to gravity.

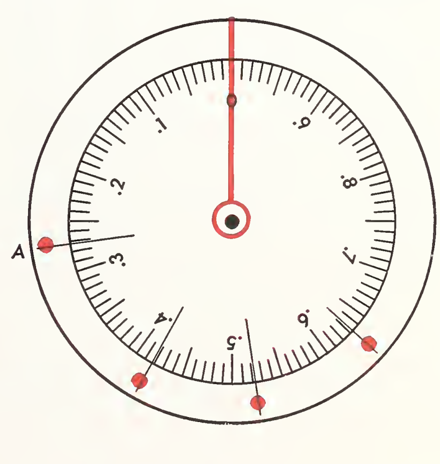


When the switch ***K*** is closed, an electric current from a battery ***V*** flows through the contact switch **C** as well as the electromagnet ***E***, holding the steel ball ***B*** in the position shown. As the turntable rotates, the front end of the rider strip ***P*** strikes the tripping switch prong at **C**, opening the electric circuit and dropping the ball. The rider strip ***P*** and the switch **C** are so located as to open the electric circuit when the zero mark on the turntable lies directly beneath the ball ***B***. A plumb line is used to align these two points. As the ball falls and the table continues to turn, the ball strikes the table surface at some point and makes a black mark as indicated at ***A***. The time of fall is therefore determined by the divided circle. Black soot can be deposited on the lower side of the ball by holding it in a candle flame.

Object. To study the laws of freely falling bodies and to determine the acceleration due to gravity.

Measurements and Data. Suppose that we have performed this experiment, dropped the ball from four different heights, and obtained the four marks shown on the disk in Fig. B. The heights ***s*** are measured with a

Fig. B. Timing table for laboratory experiment on falling bodies.



meter stick and recorded in column 2 of Table 1. The corresponding times t are measured directly from the disk and recorded in column 3.

Table 1. Recorded Data

Trial	s (cm)	t (sec)
1	36.2	.272
2	85.7	.419
3	133.5	.522
4	196.4	.633

Calculations. For calculating the acceleration due to gravity from these measurements, make a table on your laboratory report paper with the four headings as in Table 2.

Table 2. Calculated Results

Trial	$2s$ (cm)	t^2 (sec)^2	g (cm/sec^2)
1	72.4	.0740	978

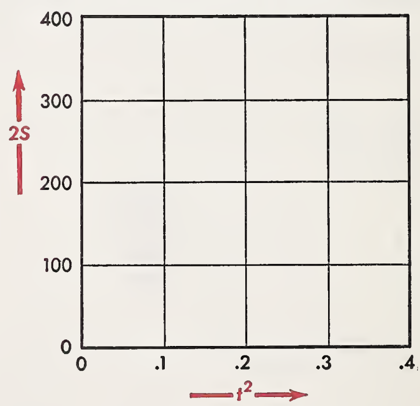
Calculations for trial 1 are already made and will serve as a guide and check upon your calculations.

By referring to Eq. (5) we see that column 2 of this table will contain a list of figures representing the numerator and column 3 will contain a list of figures representing the denominators for calculating g. To fill in column 2 for all trials, multiply the values of s in the second column of Table 1 by 2. For column 3, square the values of t recorded in column 3 of Table 1. The last column is filled in with the calculated values of g by dividing each value of $2s$ by the corresponding value of t^2. (Do not use a slide rule in these calculations, but express your results to three significant figures only.)

Results and Conclusions. Your final report should include answers to the following:

1. What is the average value for the four values of g obtained in this experiment?
2. What is the percentage error between the average value and the accepted value $g = 980$ cm/sec^2?
3. Make a graph for the data taken in this experiment, by plotting $2s$ against t^2. Cross-section paper may be used, or you can make your own chart as shown in Fig. C.

Fig. C. Cross-section chart for drawing a graph.



Mechanics | Lesson 11

PROJECTILES

This is a descriptive kind of laboratory experiment in which we are going to study the paths of projectiles and particularly how they change as we change the elevation angle.

Theory. We have seen in the preceding lesson, how, by knowing the initial velocity of projection **v** and the elevation angle θ of a body, we can calculate its range ***R***, maximum height ***H***, and time of flight ***T***. The method by which the formulas given in Table 1 of Mechanics, Lesson 10, are derived is illustrated in Fig. A.

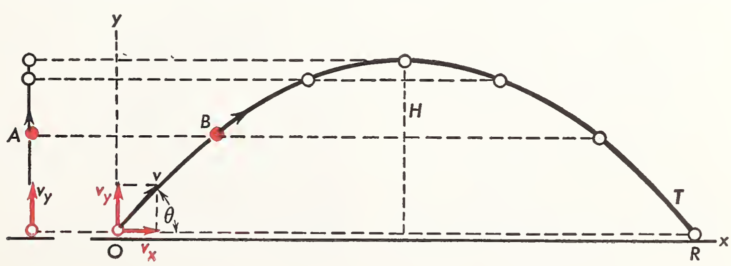
The initial velocity **v** is resolved into two components $\mathbf{v}_x$ and $\mathbf{v}_y$. We then visualize the projectile as having two motions at the same time: one is the motion of a body moving horizontally with a velocity $\mathbf{v}_x$, and the other the motion of a body projected upward with the velocity $\mathbf{v}_y$. In other words, if one projectile ***A*** is projected straight upward with a velocity $\mathbf{v}_y$ and simultaneously another projectile ***B*** is projected with the velocity **v** at the elevation angle θ, the two will rise to the same maximum height in the same time and return to strike the ground simultaneously.

Hence, by knowing **v** and θ for any projectile, one can find the y-component of the velocity $\mathbf{v}_y$ and, using the formulas for freely falling bodies, Eqs. (1), (2), (3), and (4) in Mechanics, Lesson 10, determine distances and times to any point of a trajectory. These are the basic principles from which the relations given in Table 1 of the same lesson are derived.

Apparatus and Procedure. The apparatus to be used in this experiment consists of a large flat board as shown in Fig. B. At the lower left corner, a small nozzle producing a narrow stream of water is mounted free to turn about a horizontal axis. Waterdrops, therefore, become the projectiles in our experiment. Not only does the water stream permit one to see the entire trajectory at a glance, but to observe continuously how the shape changes with the elevation angle.

The elevation angle θ of the nozzle and stream can be set to any desired angle by means of a pointer and scale, while the height and range can be measured with a meter stick or the ruled lines of the backboard. The scale of horizontal and vertical

Fig. A. The range *R*, maximum height *H*, and the time of flight of a projectile depends on the initial velocity v and the elevation angle θ.



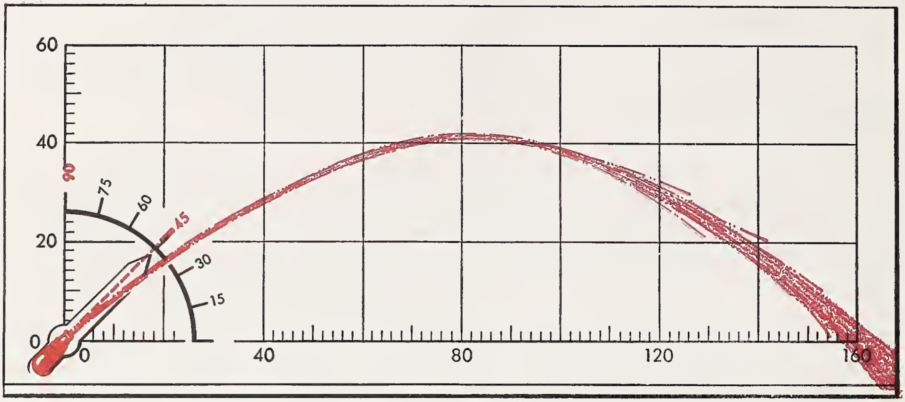


Fig. B. Diagram of water-jet experiment for studying the paths of projectiles.

lines on the backboard are in centimeters and the angles are in degrees.

To proceed with the experiment, the stream of water is turned straight up to 90° and the water valve adjusted until the stream comes up to the 80 cm mark and no higher. At this setting of the stream velocity, the angles are set at 75°, 60°, 45°, 30°, 15°, and 0° successively. For each position, the range ***R*** and the maximum height ***H*** are measured along and from the bottom line, and the values recorded on your data sheet.

Object. ***To determine the range and maximum height of a projectile for different elevation angles.***

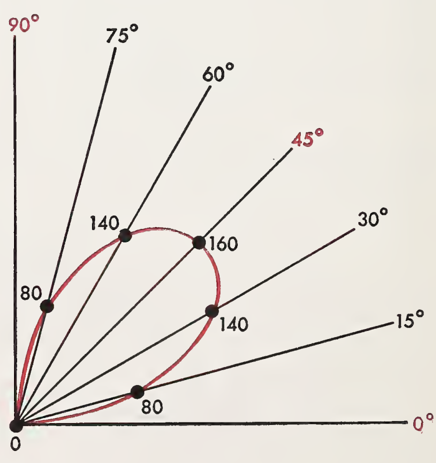
Table 1. Recorded Data

θ (deg)	H (cm)	R (cm)
90	80	0
75	75	80
60	60	140
45	40	160
30	20	140
15	5	80
0	0	0

Measurements and Data. As this experiment is performed, the measurements should be recorded in a table of three columns. Suppose we have followed the specific instructions given above, the recorded data would be as given in Table 1.

Calculations. Using the maximum range ***R*** and the height ***H*** for elevation angle $\theta =$ 45°, calculate the initial velocity of the water stream from the nozzle in this experiment. Use the relations given for a 45° ele-

Fig. C. A polar graph for the range of a projectile.



vation angle in Table 1 of Mechanics, Lesson 10.

Results and Conclusions. Draw two graphs of the data taken in this experiment. In the first graph, plot the elevation angles θ horizontally from 0° to 90° and the maximum heights H vertically from 0 to 80 cm. For the second graph, plot the elevation angles θ from 0° to 90° and the ranges R vertically from 0 to 160 cm.

For your conclusions answer the following questions:

1. At what elevation angle is the greatest range attained?
2. At what elevation angle is the maximum height attained?

Where angles are involved in the plotting of graphs, it is sometimes informative to plot what is called a ***polar graph***. Such a graph is shown in Fig. C for the range data taken in this experiment. The radial lines from the origin **O** are drawn at the proper elevation angles while the ranges R are measured out along these radial lines. Such a graph shows that there is a maximum range and that there is symmetry about this angle.

Mechanics | Lesson 13

THE FORCE EQUATION

Theory. Our laboratory experiment in this lesson is concerned with Newton's Second Law of motion as expressed by the ***force equation.***

$$F = ma \tag{1}$$

In its simplest terms, this law says that if you apply a constant force F to a given mass m, it will move with a uniform acceleration a, given by the relation that F equals the product of m times a. These three measurable quantities are represented schematically in Fig. A.

The three systems of units in which F, m, and a are commonly measured are

F	m	a
newtons	kg	m/sec^2
dynes	gm	cm/sec^2
lb	slugs	ft/sec^2

We have seen in Mechanics, Lesson 12, that the weight W of an object is simply a measure of the force F with which the earth pulls downward on any given mass m, and if no other force acts on a body, it will fall freely with an acceleration g. For this special case, one usually writes

$$W = mg \tag{2}$$

it being understood that this is Newton's second law and in reality is Eq. (1).

To find the weight of an object multiply its mass by g, the acceleration due to gravity. To find the mass of any object, divide its weight by g.

$$g = 9.80 \frac{\text{m}}{\text{sec}^2}$$

$$g = 980 \frac{\text{cm}}{\text{sec}^2}$$

$$g = 32 \frac{\text{ft}}{\text{sec}^2}$$

We have seen in our laboratory experiment in Mechanics, Lesson 4, that to determine the acceleration of a body, we

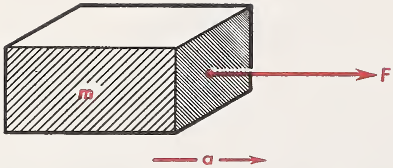


Fig. A. Illustration of the force equation $F = ma$.

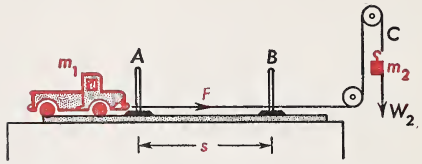


Fig. B. Laboratory experiment for measuring the acceleration of a toy truck due to a known force.

measure the distance traveled and the time of travel and make use of the kinematic equation $s = \frac{1}{2}at^2$. Since a similar procedure will be followed in this experiment, we will use this same equation.

Upon transposing, we obtain the more useful form

$$\boxed{a = \frac{2s}{t^2}} \qquad (3)$$

Apparatus. The apparatus in this experiment is easily secured and set up. It consists of a toy truck with ball-bearing wheels* and a strip of plate glass about 1 ft wide and 6 ft long. See Fig. B. A strong thread, fastened to the front of the car, passes over two laboratory type ball-bearing pulley wheels to a small mass at **C**.

Object. *To study the dynamics of motion and Newton's Second Law of Motion.*

Measurements. The truck is first put on a balance and its mass determined in kilograms. It is then put on the glass plate, and a number of small weights are added to the car body to bring its total mass to exactly 2.0 kg. This makes the total moving mass $m = 2.000$ kg.

Now with the thread attached at **A**, take a small piece of wire or solder and fasten it to the other end of the thread at **C**. Adjust this mass until the car moves along the glass track to the right with uniform speed. The force due to the earth's pull on this mass is just sufficient to overcome friction, yet it produces no acceleration.

The next step is to remove a 20-gm mass m_2 from the truck and add it to **C**. The car is then allowed to accelerate, starting from rest at the end of the track at **A**. With a stop watch, measure the time t it takes to go from **A** to **B**, and with a meter stick, measure the distance **s**. Record the data in a table of five columns as shown in Table 1.

An additional 20-gm mass should be removed from the truck and added at **C**. Again the time to travel a given distance should be determined and recorded. A third 20-gm mass should be removed and the measurements repeated again.

As a fourth trial, increase the total truck mass by 500 gm and repeat the experiment with $m_2 = 60$ gm. As a fifth and last trial, increase the truck's mass by another kilogram and repeat the acceleration measurements with $m_2 = 60$ gm.

It should be noted that although the accelerating force F acting on the truck is equal to W_2, and $W_2 = m_2g$, the total mass that undergoes acceleration is the mass of the truck plus the mass at **C**. Hence in testing the force equation, $F = ma$, the total moving mass must be used, and this is m, or $m_1 + m_2$.

Data. Suppose that we have performed the experiment as described above and have recorded the data as shown in Table 1.

* A 2- to 3-lb truck purchased at any toy store is a satisfactory vehicle. Replace the customary rubber wheels with the ball-bearing hubs of two front bicycle wheels.

Table 1. Recorded Data

Trial	m_1 (kg)	m_2 (kg)	s (m)	t (sec)
1	1.980	0.020	1.40	5.4
2	1.960	0.040	1.40	3.8
3	1.940	0.060	1.40	3.1
4	2.440	0.060	1.40	3.5
5	3.440	0.060	1.40	4.1

Calculations. To make your calculations and test Newton's Second Law of Motion, make a table of six columns and give them headings as follows:

Table 2. Calculated Results

Trial	$m_1 + m_2$ (kg)	m_2g (newton)	$1/m$ (1/kg)	$2s/t^2$ (m/sec^2)	m_2g/m (m/sec^2)
1	2.000	0.196	0.500	0.096	0.098

The row of numbers under the headings are for the first trial only, and may be used as a guide for your calculations for the other four trials. If the force equation is valid, the measured and theoretical values for the acceleration a, as given in the last two columns, should be the same for each trial.

Results. To complete your laboratory report, two graphs should be drawn from your results. One is already plotted in Fig. C, and the other is left for you to do. In Fig. C, the applied force F is plotted vertically against the measured acceleration a

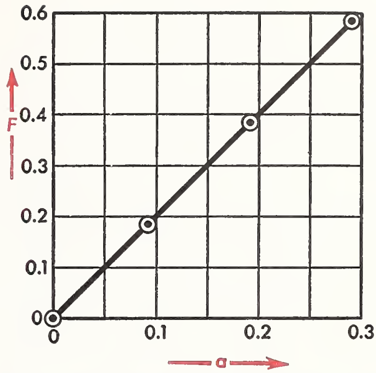


Fig. C. A graph of some experimental results showing that force *F* is proportional to acceleration *a*, mass remaining constant.

for trials 1, 2, and 3, where the mass m remained constant.

For your second graph, plot the measured a vertically against $1/m$ horizontally, for the last three trials, where F remained constant.

Conclusions. The fact that a very straight line can be drawn through the plotted points in Fig. C shows that F is proportional to a. This means that

$$F \propto a$$

and that m is the proportionality constant.

$$F = ma$$

What similar conclusions can you draw from your second graph?

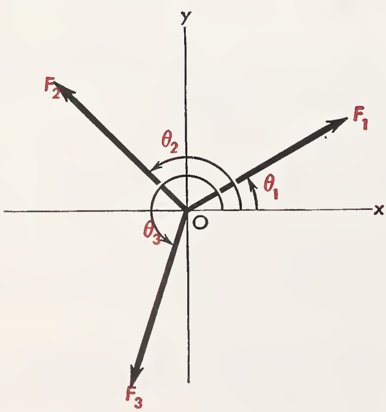
Mechanics | **Lesson 16**

CONCURRENT FORCES

Our laboratory experiment for this lesson is concerned with forces acting on a body in equilibrium. To be technical, we are concerned with the special case of three ***concurrent, coplanar forces.*** Concurrent forces are those forces whose lines of action intersect at a common point, while the term coplanar specifies that they all lie in the same plane. Most common force problems, but by no means all of them, are of this type.

Theory. Let three concurrent, coplanar, forces act on a single body as shown in Fig. A. The directions of the forces F_1, F_2, and F_3 are all measured from the **x**-axis in degrees and are designated θ_1, θ_2, and θ_3 respectively. If we make vector diagrams for these three forces, they should be drawn to scale as shown in Fig. B. If the forces are in equilibrium, their vector sum, as shown in Fig. B, will form a closed triangle with a zero resultant.

Fig. A. Diagram showing the direction angles of three concurrent, coplanar forces.



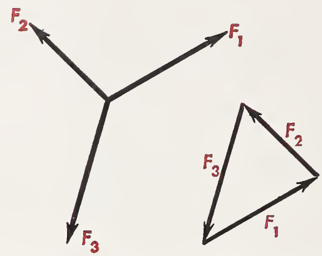
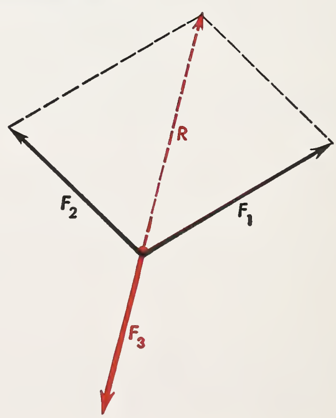


Fig. B. Vector diagrams of three forces in equilibrium.

Start now with the left-hand diagram, apply the parallelogram method of vector addition to F_1 and F_2 alone, and find their resultant. As shown in Fig. C, this vector resultant R is equal in magnitude but opposite in direction to F_3. This must be true, since R is equivalent to $\vec{F}_1 + \vec{F}_2$ and can replace them. With R and F_3 acting on a body alone, these two forces could only produce equilibrium if they are equal and opposite. R is therefore called a ***resultant,*** and F_3 can be thought of as the ***equilibrant.***

Fig. C. The resultant force R is equal and opposite to the equilibrant force F_3.



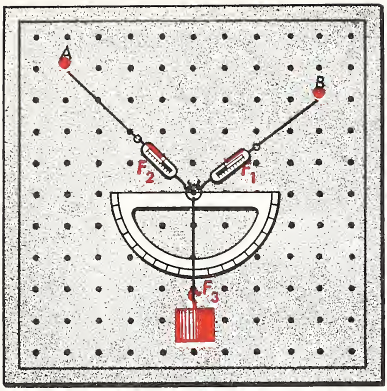


Fig. D. Experimental arrangements of spring scales and weights on pegboard.

By making similar diagrams, it can be shown that the resultant of $\vec{F}_2 + \vec{F}_3$, when reversed in direction to become the equilibrant of these two forces, is just the remaining force F_1.

Apparatus and Procedure. The apparatus in this experiment consists of a pegboard with two spring scales, several cords of different lengths with hooks at both ends, two spring scales reading pounds weight, and a small metal ring as shown in Fig. D. A large protractor should be used for measuring angles.

In performing the experiment, several trials should be made. Different points of suspension, different cord lengths, and different loads should be tried.

***Object.** To apply the principles of vector addition to find the resultant and equilibrant of two forces acting at an angle to each other.*

Measurements and Data. As a first trial, select two cords and mount them from two selected points ***A*** and ***B*** on the pegboard. Be sure the scale casing of each of the scales is at the upper end. Bring the two scale plunger hooks together at the ring and suspend a 3-lb load from the ring for F_3. Read and record the spring scale readings in Table 1, made up of seven columns. Using the protractor, measure the direction angles for each of the three forces, and record.

Repeat this experiment by changing cords and points ***A*** and ***B***. Increase the load to 5 lb and make recordings as before. Change initial conditions again and make a third trial with a load of 8 lb.

Recording the data you have taken in this experiment as shown in Table 1, you would then have completed the experiment, and be ready for your calculations and results.

Table 1. Recorded Data

Trial	F_1 (lb)	θ_1 (deg)	F_2 (lb)	θ_2 (deg)	F_3 (lb)	θ_3 (deg)
1	4.7	37.0	3.8	176.5	3.0	270
2	3.1	29.0	4.3	126.0	5.0	270
3	5.2	62.0	4.1	127.0	8.0	270

Calculations and Results. To complete the laboratory report, you will need a table of five columns with headings like those shown in Table 2.

Table 2. Calculations and Results

Trial	Resultant R	Equilibrant F_3	θ_R	$\theta_3 - 180°$
1	2.9	3.0	91.0	90

The results for the first trial are filled in for comparison and check purposes. The procedure carried out for these tabulated results is shown in Fig. E, and should be repeated for your report. Using a sharp pencil, a centimeter ruler, and a protractor, lay out ***x***- and ***y***-axes on a sheet of paper. Draw both F_1 and F_2 at their proper angles

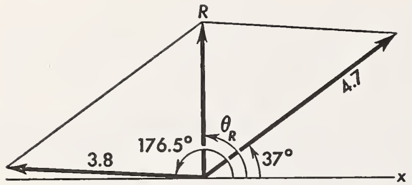


Fig. E. Graphical construction for trial 1 in this experiment.

θ_1 and θ_2 respectively. Graphically, find their resultant force and call it ***R***. Measure the length of ***R*** and the angle it makes with the ***x***-axis and tabulate in the second and fourth columns respectively. Write in $\boldsymbol{F}_3$ directly from your data in Table 1, and in the last column record the direction $\theta_3 - 180°$. The magnitude of the resultant ***R*** should be the same as the magnitude of $\boldsymbol{F}_3$, and the angle θ_R should be the same as the value of $\theta_3 - 180°$, shown in the last column.

Repeat this graphical construction for trials 2 and 3, and make similar measurements of lengths and angles, and record in Table 2. Because of the nature of the equipment used in this experiment, errors of about 5% are well to be expected between the graphical data and the recorded data.

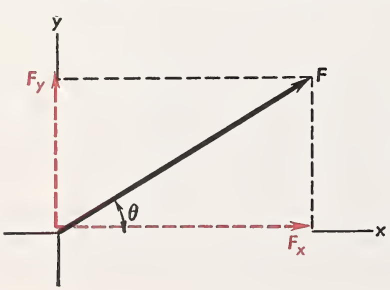
Conclusions. Make a short statement in your own words of what you have learned from this experiment as regards the equilibrium of a body acted upon by three forces.

***Mechanics* | Lesson 18**

RESOLUTION OF FORCES

Many problems in mechanics are quite easily solved by the resolution of a force into components. The principles involved in such procedures are demonstrated by a number of illustrations and examples in the preceding lesson. In our laboratory experiment we are going to set up two different objects, apply different sets of forces, and employ the principles of components to verify the results.

Fig. A. A force ***F*** is resolved into two component forces F_x and F_y.



Theory. Suppose that a single force ***F***, acting at an angle θ with the ***x***-axis, is resolved into two components $\boldsymbol{F}_x$ and $\boldsymbol{F}_y$, as shown in Fig. A. We have seen that the magnitudes of these two components are given by Eq. (2) of Mechanics, Lesson 17, as

$$\boxed{\begin{aligned} F_x &= F\cos\theta \\ F_y &= F\sin\theta \end{aligned}} \qquad (1)$$

Now, if the magnitudes of these forces are kept the same but their directions are reversed, as shown in Fig. B, we obtain the two forces ***H*** and ***V*** as indicated. If we apply these three forces ***F***, ***H***, and ***V*** to a body equilibrium is automatically established. The resultant of $\boldsymbol{F}_x$ and $\boldsymbol{F}_y$ is ***F***, and the resultant

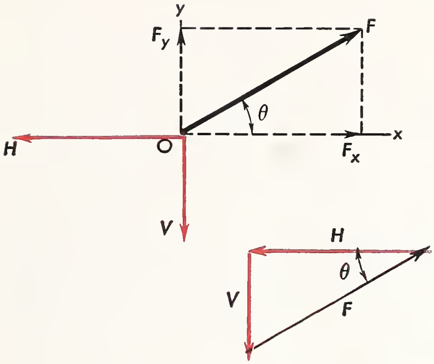


Fig. B. If the components of any force *F* are reversed in direction, the components and the original force have a vector sum of zero.

of ***H*** and ***V*** is equal and opposite to ***F***. We are therefore imposing the fundamental principle that equal and opposite forces acting on the same body are in equilibrium, and conclude that if the components of any given force are reversed in direction, the components and the original force have a vector sum of zero.

Since kilogram weights are to be used to produce the applied forces in this experiment, we will employ the force equation in the form

$$\boxed{W = mg} \tag{2}$$

Whenever a mass is recorded in kilograms we will multiply by 9.8 m/sec², the acceleration due to gravity, to obtain the force in newtons.

Apparatus and Measurements. This experiment is performed in two parts.

Part 1. Suspend three hooked weights with cords from two pulleys and a ring, all fastened to a pegboard as shown in Fig. C. A fixed pin at the center of the board holds the ring in place while the three sets of weights are adjusted.

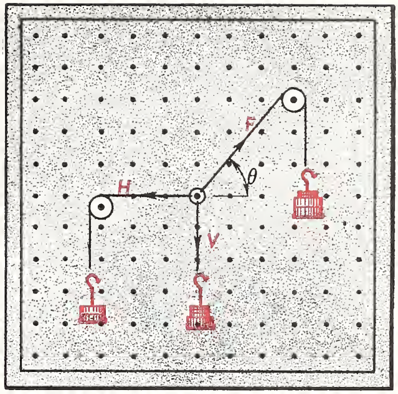


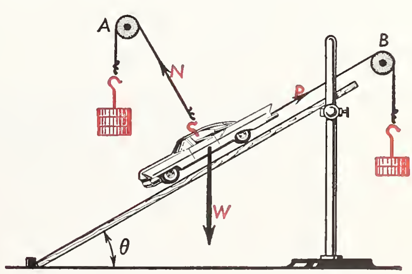
Fig. C. Experimental arrangement for measuring force components on a pegboard.

Begin by placing a 2.5-kg mass on the upper hook for ***F***. Now add weights for ***H*** and ***V***, and adjust the top pulley position if necessary until the ring is centered and free of the pin. When this is accomplished the angle θ is measured with a large protractor and recorded, along with the three weights.

For the recording of data you should make a table of five columns on your data sheet, and head the columns as shown in Table 1. All masses should be recorded in kilograms and multiplied by 9.8.

For a second trial change both ***F*** and the pulley position, and then alter ***H*** and ***V*** until the ring is again free of the centering pin. Record both the angle and the three weights in the same table.

Fig. D. Experimental arrangement for measuring force components on an inclined plane.



Part* 2.** In this experiment a toy automobile, whose mass has been determined by weighing, is supported on an inclined board by a single cord passing over a pulley ***B to a weight as shown in Fig. D. With the incline angle θ set at some value the right-hand weights are adjusted until the car accelerates neither up nor down the incline.

A second cord is now hooked to the top of the car and over a pulley to another set of hooked weights. These weights are changed until the wheels just barely lift from the incline, and the direction of ***N*** is at right angles to the surface.

Under these conditions the inclined plane can be removed if desired. In any case record the angle θ, the magnitudes of ***P*** and ***N***, and the weight of the car. A second table of five columns should be made, with headings as shown in Table 2.

For your second trial change the angle θ and again secure balance by adjusting the pulleys and weights. Record the values in Table 2.

Object. ***To apply the principles of equilibrium to find two components of a single force.***

Data. Suppose we have made two trials for each of the two experiments just described, and have recorded the data as shown in Tables 1 and 2.

Table 1. Recorded Data for Pegboard Experiment

Trial	θ (deg)	*F* (newtons)	*V* (newtons)	*H* (newtons)
1	38	2.5×9.8	1.52×9.8	1.95×9.8
2	54	3.5×9.8	2.84×9.8	2.05×9.8

It now remains for you to determine whether ***H*** and ***V*** have magnitudes equal to the horizontal and vertical components of ***F***, and whether ***P*** and ***N*** have magnitudes equal to the parallel and normal components of ***W***.

Table 2. Recorded Data for Inclined Plane Experiment

Trial	θ (deg)	W (newtons)	P (newtons)	N (newtons)
1	35°	1.2×9.8	0.69×9.8	0.98×9.8
2	40°	1.2×9.8	0.78×9.8	0.93×9.8

Calculations. Make two tables of five columns each and with headings as shown in Tables 3 and 4. Trial 1 for Part 1 has been calculated and recorded as a check upon your procedure. Carry out the calculations for the other three trials.

Table 3. Calculations for Pegboard Experiment

Trial	F sin θ (newtons)	V (newtons)	F cos θ (newtons)	H (newtons)
1	15.1	14.9	19.3	19.1

Table 4. Calculations for Inclined Plane Experiment

Trial	W sin θ (newtons)	P (newtons)	W cos θ (newtons)	N (newtons)

Reading across each row in the completed tables the values in columns 2 and 3 should agree with each other, and the values in columns 4 and 5 should also agree. Any differences between them are due to experimental errors such as friction in the pulleys, inaccuracy of the weights used, protractors, etc.

Results and Conclusions. In your final report make a brief statement of what you have learned from this experiment.

Mechanics | **Lesson 20**

PARALLEL FORCES

The general principles of the equilibrium of a rigid body are so useful in the solving of so many mechanical problems that we should become more familiar with the concepts involved. There is no better way to do this than to perform a laboratory experiment with apparatus similar to that used in this lesson.

Theory. If forces are to be applied to a rigid body and translational equilibrium is to be established, we can begin by applying the first condition of equilibrium, namely,

$$\boxed{\Sigma F_x = 0} \quad (1)$$

$$\boxed{\Sigma F_y = 0} \quad (2)$$

where ΣF_x represents the sum of all the x-components of all the forces, and ΣF_y the sum of all the y-components of the same forces. See Mechanics, Lesson 19.

If rotational equilibrium is to be established we would apply the second condition of equilibrium, namely,

$$\boxed{\Sigma L = 0} \quad (3)$$

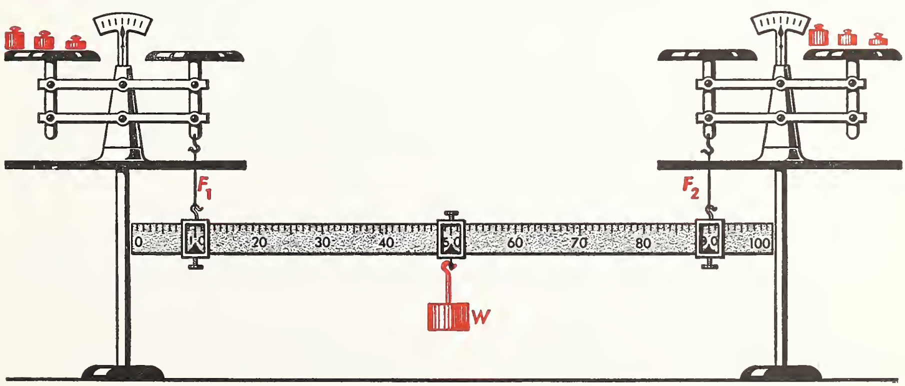
where ΣL represents the sum of all the applied torques. Each torque is given by the force F times its lever arm d.

$$L = F \times d \quad (4)$$

Torques tending to rotate a body counterclockwise about a pivot point are positive, while those tending to turn it clockwise are negative.

Apparatus. The apparatus to be used in this experiment is illustrated in Fig. A. It consists of two platform balances of the laboratory type, a meter stick, and several sets of gram and kilogram weights. The rigid body in this arrangement is the meter stick, and the applied forces are F_1, F_2, and W. The upward forces F_1 and F_2 are measured by the platform balances, and the downward force W is determined by the known weight suspended from a hook located anywhere along the meter stick. The

Fig. A. Arrangement of apparatus for the laboratory experiment on parallel forces in equilibrium.



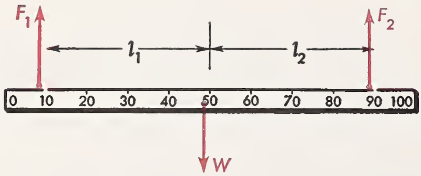


Fig. B. Isolated diagram of forces acting on the meter stick used in this experiment on equilibrium.

geometry of the arrangement is more simply represented in Fig. B.

Object. *To study the relations between forces and torques that produce translational and rotational equilibrium.*

Measurements. The meter stick is first suspended from the scales by hooks and cords located at the 10-cm and 90-cm marks, respectively. Weights are then added to each scale pan to restore the balance. Since these weights take care of the weight of the meter stick, they need not be recorded.

Place a hook or slider on the meter stick at the 50-cm mark and suspend from it a 1-kg weight. Now add weights to the scale platforms and restore balance to each of the two scales.

Construct a table of seven columns as shown in Table 1, and record all masses in kilograms and all distances in meters. As mass is recorded, insert × 9.8 after each one to be sure that all forces are in the proper units of newtons. Also, in recording **W**, be sure to weigh the hook or slider and add its mass to that of the suspended 1-kg weight.

Move the load **W** to the 40-cm mark on the meter stick and repeat the balancing of the scales and the recording of data under trial 2. Make two additional trials by setting **W** on the 30-cm mark, and finally on the 20-cm mark.

Data. Suppose we have performed the experiment as it is described above and recorded the data shown in Table 1.

Calculations and Results. We now wish to apply the first and second conditions of equilibrium, as given by Eqs. (1), (2), and (3), to the recorded data. First of all we notice that all three forces are parallel to each other and vertical. Since the **x**-components of all three forces are therefore

Table 1. Recorded Data

Trial	Weight Position	l_1 (m)	l_2 (m)	F_1 (newtons)	F_2 (newtons)	W (newtons)
1	.50	.40	.40	.516 × 9.8	.518 × 9.8	1.035 × 9.8
2	.40	.30	.50	.645 × 9.8	.389 × 9.8	1.035 × 9.8
3	.30	.20	.60	.775 × 9.8	.259 × 9.8	1.035 × 9.8
4	.20	.10	.70	.905 × 9.8	.129 × 9.8	1.035 × 9.8

mass of slider hook = 0.035 kg

Table 2. Calculations and Results

Trial	F_1 (newtons)	F_2 (newtons)	W (newtons)	$F_1 + F_2$ (newtons)	$F_1 \times l_1$ (newton m)	$F_2 \times l_2$ (newton m)
1	5.06	5.08	10.14	10.14	2.02	2.03

zero, Eq. (1) is satisfied. The remaining two equations are best applied to the data by tabulation of the separate factors. For this purpose construct a table of seven columns with headings as shown in Table 2. The calculations for trial 1 are already recorded, and will serve as a guide and check on your calculations for the other three trials.

The second, third, and fourth columns are applied to Eq. (2) and are a test for translational equilibrium. To interpret these results it can be seen from Fig. B that F_1 and F_2 are both upward, and therefore positive, while W is downward and therefore negative. For this experiment Eq. (2) becomes

$$F_1 + F_2 - W = 0$$

or

$$F_1 + F_2 = W$$

This equation tells us that reading across each row, values in columns 4 and 5 should be the same. The last two columns are derived from Eq. (3) and are a test for rotational equilibrium. For this experiment Eq. (3) can be written

$$L_1 + L_2 + L_3 = 0$$

Since we are free to chose a pivot point, we select for each trial the point at which W is applied to the meter stick. This eliminates L_3 as a torque since W then has no lever arm. Around this pivot, however, F_1 exerts a clockwise torque while F_2 exerts a counterclockwise torque. Consequently we may write

$$-F_1 \times l_1 + F_2 \times l_2 = 0$$

or

$$F_2 \times l_2 = F_1 \times l_1$$

Reading across each row, the torques in column 6 should be the same as the torques in column 7.

Conclusions. Make a brief statement in your final report of what you have learned from this experiment as regards equilibrium.

***Mechanics* | Lesson 22**

THE SIMPLE CRANE

The engineering design of many large and small structures depends upon the mechanics of forces in equilibrium. Some of the most important problems are concerned with the equilibrium of rigid bodies, problems to be found in this experiment on the simple crane.

Theory. A body at rest or moving with constant velocity is in equilibrium. To be in equilibrium the forces acting on a rigid body must satisfy two conditions. To be in translational equilibrium the sum of all the forces must be equal to zero, and to be in rotational equilibrium the sum of all the torques must be equal to zero.

Apparatus. The simple crane takes the form shown in Fig. A, and consists of a vertical member K called the king post, a movable member B called the boom, a cable or rope T called the tie rope, and a heavy object W to be lifted called the load. Several sets of gram and kilogram weights are used for the applied forces.

The movable boom of the crane is the rigid body in this experiment, and when it is in any position the problem becomes one

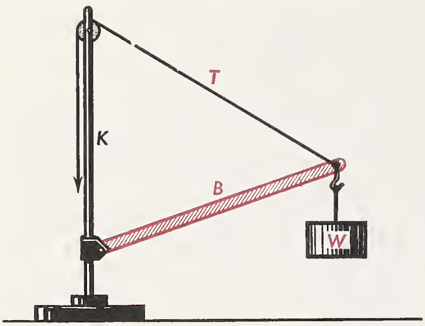


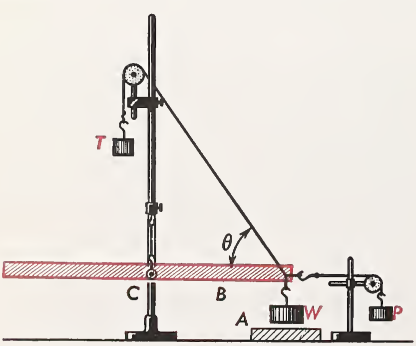
Fig. A. A simple crane for lifting a heavy load.

of finding the tension in the tie rope ***T***, and the compression force acting at the outer end of the boom. To simplify the experiment we eliminate the weight of the boom from consideration by using a uniform wooden timber about one meter long and balancing it in a horizontal position as shown in Fig. B.

Object. *To apply the principles of components and the principles of equilibrium to the simple crane.*

Procedure and Measurements. The boom is pivoted at its center of gravity **C** as shown in the diagram. A 2.5-kg load ***W*** is suspended from one end and a block ***A*** placed under it to keep the beam horizontal. Two cords are then fastened to the end of the boom, one passing over a pulley on the king post to a hook and weight ***T***, and the other horizontally over a table pulley to a hook and weight ***P***. The tie-rope pulley should be high up on the king post so the angle θ is about 65°.

Fig. B. Arrangement of apparatus in experiment on the simple crane.



The pivot hole in the boom at **C** should be about one-half in. larger than the pin, and a cord fastened to a clamp on the king post should be used to lift the boom free of the pin. The weight ***P*** is increased until the pivot hole is centered around and completely free of the pin as shown. The weight ***T*** is then increased until the load ***W*** is just lifted free of the block ***A*** as shown. Continue readjusting ***T*** and ***P*** until the boom is free at **C**.

When complete balance is acquired, the data should be recorded in a table of four columns with headings as shown in Table 1. With a large protractor, the tie-rope angle θ is measured and recorded in column 1. The three weights are then recorded in the other three columns, and since they are specified in kilograms, each should be multiplied by 9.8, the acceleration due to gravity. These products give each of the forces in the proper mks units of newtons.

Remove the weights, lower the tie-rope pulley, and change the load to 2.0 kg. Add weights ***T*** and ***P***, and again obtain free suspended equilibrium of the boom. Again measure the angle θ and record the three forces as a second trial.

Make two more trial adjustments of the apparatus, each time lowering the tie-rope pulley, decreasing the load ***W*** by 0.5 kg, and recording the data.

Data. Assume that the above experiment has been performed and the data has been recorded as shown in Table 1.

Calculations. Since the weight of the boom has been eliminated from the calcula-

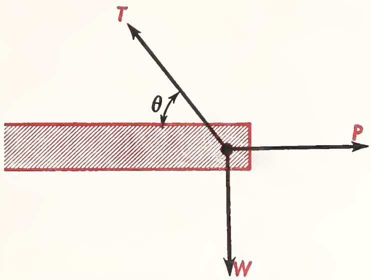


Fig. C. Three forces act through a common point at the end of the boom.

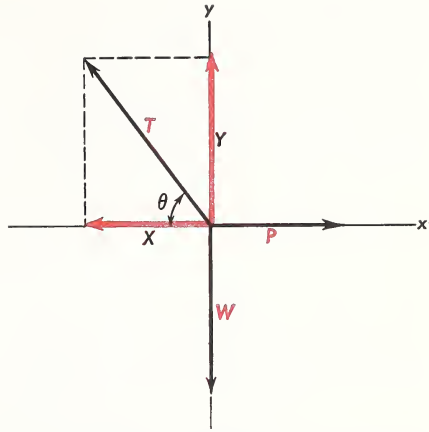


Fig. D. The components of T should be equal and opposite to P and W.

Table 1. Recorded Data

θ (deg)	W (newtons)	T (newtons)	P (newtons)
65°	2.5 × 9.8	2.75 × 9.8	1.17 × 9.8
58°	2.0 × 9.8	2.37 × 9.8	1.26 × 9.8
51°	1.5 × 9.8	1.94 × 9.8	1.23 × 9.8
42°	1.0 × 9.8	1.50 × 9.8	1.12 × 9.8

tions by counterbalancing, equilibrium conditions involve only the three concurrent forces acting at the end of the boom. These forces are shown in Fig. C are **T**, **P**, and **W**.

Here we apply the principles developed in Mechanics, Lesson 18, of resolving the force **F** into **x**- and **y**-components as shown in Fig. D. These components **X** and **Y**, if reversed in direction, should be equal to the measured forces **P** and **W**, respectively. From the right triangle having the base angle θ, we can write

$$\sin \theta = \frac{Y}{T} \qquad \tan \theta = \frac{Y}{X}$$

Since equilibrium requires **X** to be equal to **P**, and **Y** to be equal to **W**, we can substitute and obtain

$$\sin \theta = \frac{W}{T} \qquad \tan \theta = \frac{W}{P}$$

Solving the first equation for **T** and the second for **P**, we find

$$\boxed{T = \frac{W}{\sin \theta}} \tag{1}$$

$$\boxed{P = \frac{W}{\tan \theta}} \tag{2}$$

Now we can compare the measured values of **T** and **P** with **W** by means of these equations. For this purpose make a table of six columns as shown in Table 2, and fill in the columns for all four trials. The calcu-

Table 2. Calculated Results

W (newtons)	θ (deg)	W/sin θ (newtons)	T (newtons)	W/tan θ (newtons)	P (newtons)
24.5	65.0	27.0	26.9	11.4	11.5

lated results for the first trial are already filled in as a guide and check on your methods of calculation.

Equilibrium requires the values in columns 3 and 4 to be the same, and those in columns 5 and 6 to be the same. Any differences between them should not be over 3%, and are due to experimental errors.

Conclusions. Make a brief statement in your report of what you have learned from this experiment.

Mechanics | **Lesson 25**

COEFFICIENT OF FRICTION

The coefficient of sliding friction was defined in the last lesson as the ratio between two forces, the force of friction and the force pushing two surfaces together. As shown in Fig. A, the force of friction is the force ***f*** required to pull the mass ***m*** along the surface with constant velocity, and the force pushing the surfaces together is the normal force ***N***. By definition, we write

$$\boxed{\mu = \frac{f}{N}} \qquad (1)$$

The coefficient of rolling friction is defined in the same way and is given by the same formula, Eq. (1). For the illustration in Fig. B, ***f*** is the horizontal force pulling the wheel along, and ***N*** is the normal force pushing the wheel down against the road.

Theory. The method we are going to use to measure the coefficient of sliding friction is to place a block on an inclined plane and then tilt the plane until the block slides down with constant velocity. See Fig. C. When this condition exists, Eq. (1) can be imposed directly upon the components of the weight ***W***. The component ***F*** is equal in magnitude to ***f***, the sliding friction, and the component ***N*** is the normal force pushing the two surfaces together. If θ is the angle of the incline, then

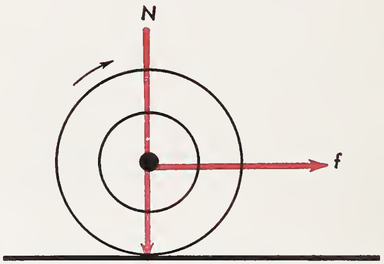


Fig. B. The coefficient of rolling friction depends upon *f* and *N*.

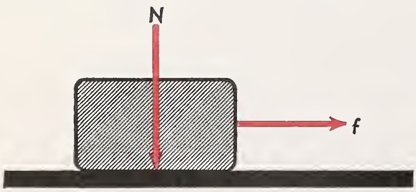


Fig. A. The coefficient of friction depends upon *f* and *N*.

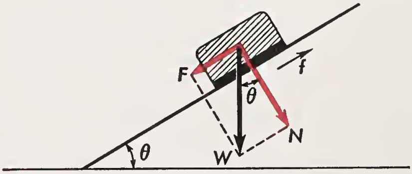


Fig. C. Illustrating the angle of uniform slip for a block on an inclined plane.

$$\mu = \frac{f}{N}$$

or

$$\mu = \frac{F}{N} \quad (2)$$

From the right triangle in Fig. C, it is clear that

$$\frac{F}{N} = \tan\theta \quad (3)$$

Therefore, we can write

$$\boxed{\mu = \tan\theta} \quad (4)$$

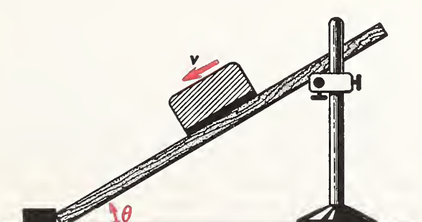
where θ is the so-called ***angle of uniform slip.***

Apparatus and Procedure. ***Part 1.*** The apparatus for measuring the angle of uniform slip is composed simply of a number of smooth, straight boards of different kinds of wood, and several smooth wooden blocks. Various materials such as sheet rubber and metal can be fastened or glued to the flat surfaces of some of the blocks and used in the experiment.

A board such as walnut is selected and tilted up against a support as shown in Fig. D. Any block is then placed on the board and the angle θ increased or decreased until the block slides down with a slow but uniform speed. Although the sliding surfaces are not perfectly uniform and the block will slow down and speed up, careful observation enables one to set the angle with considerable precision. The angle θ is then measured with a large protractor and recorded in a table of two columns as shown in Table 1.

The experiment should be repeated a number of times with different combinations of boards and blocks. For each one, only a note as to the surfaces in contact and the angle θ need be recorded as shown. A shoe placed on any one board should give an interesting result.

Fig. D. Apparatus for determinng the coefficient of sliding friction.



Part 2. The apparatus for measuring the coefficient of rolling friction is shown in Fig. E. It consists of a small toy truck with ball-bearing wheels mounted free to roll along a plate of glass. The car is first weighed to find its total mass M, and hence the normal force N. A thread passing over two pulleys to a small mass m is used to measure f, the force of friction. A spirit level should be used to get the glass plate level, and the mass m should be carefully altered until the truck moves along with constant speed. Record the data in a table of three columns as shown in Table 2.

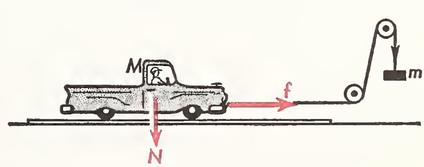
As a second trial, cover the glass plate with a strip of felt or velvet fabric, and increase m until uniform velocity is attained. Record as before in Table 2.

Similar trials can be made with another small toy car having rubber-tired wheels.

Object. ***To determine the coefficients of sliding friction and the coefficients of rolling friction for various objects and materials.***

Measurements and Data. After both parts of this experiment have been per-

Fig. E. Laboratory experiment for determining the coefficient of rolling friction.



formed, the recorded data should appear as shown in Tables 1 and 2.

Table 1. Sliding Friction Data

Materials	θ (degrees)
pine on pine	19.0
oak on oak	14.0
maple on maple	16.5
walnut on walnut	13.0
steel on oak	14.5
rubber on oak	17.5

Table 2. Rolling Friction Data

Objects	M (kg)	m (kg)
truck with ball-bearing wheels on glass	1.54	.006
truck with ball-bearing wheels on velvet	1.54	.090
car with rubber-tired wheels on glass	0.85	.025
car with rubber-tired wheels on velvet	0.85	.070

Calculations and Results. For your calculations and your report make two tables with headings as shown in Tables 3 and 4.

The results of the first trial for each of Parts 1 and 2 are included, and will serve

Table 3. Coefficient of Sliding Friction

Materials	μ
pine on pine	.34

Table 4. Coefficient of Rolling Friction

Objects	μ
ball-bearing truck on glass	.0039

as a guide in completing the table. Note in Fig. E that $f = mg$ and $N = Mg$, and that when these two quantities are substituted in Eq. (1),

$$\mu = \frac{mg}{Mg}$$

we obtain simply

$$\mu = \frac{m}{M} \tag{5}$$

This equation should be used for Part 2.

Conclusions. Under this heading in your final report, answer the following questions:

1. What surfaces in your experiment have the smallest coefficient of sliding friction?
2. What effect do each of the following have upon rolling friction:
   (a) a soft road surface, (b) a hard road surface, (c) hard wheels, (d) soft wheels, and (e) ball-bearing wheels?

Mechanics | Lesson 28

CENTER OF GRAVITY

In our previous lesson the concepts of center of mass and center of gravity were introduced as an important part of the development of mechanics. It is the purpose of this lesson to set up a number of combinations of masses of different shapes and to determine experimentally their centers of gravity.

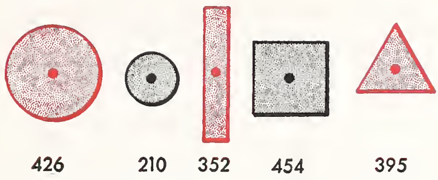


Fig. A. Object shapes used in this experiment on the center of gravity.

Theory. The center of mass of any body or system of bodies is defined as a point at which all of the mass of the body may be considered as concentrated. Similarly the center of gravity of a body or system of bodies is a point at which all of the weight of a body may be considered as concentrated. The center of gravity of all regular shaped bodies, like those shown in Fig. A, are located at their geometrical center.

If two such bodies are located some fixed distance apart, as shown in Fig. B, the two considered as a system will have a center of gravity **C** lying somewhere along the straight line joining their centers.

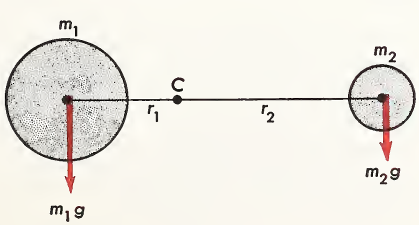
The center of gravity is given by the relation that

$$m_1g \times r_1 = m_2g \times r_2 \qquad (1)$$

In other words, **C** is a point at which the body is in rotational equilibrium and will produce balance. The clockwise torque $m_2g \times r_2$ is equal to the counterclockwise torque $m_1g \times r_1$. If we cancel the **g**'s on both sides of the equation, we obtain

$$\boxed{m_1 \times r_1 = m_2 \times r_2} \qquad (2)$$

Fig. B. Illustrating the center of gravity, point C, for a system of two bodies.



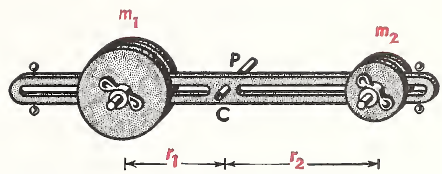


Fig. C. Apparatus for finding the center of mass of a system of bodies.

which is the relation for the identical point, the center of mass.

Object. ***To find the center of gravity of several systems of regularly and irregularly shaped objects.***

Apparatus. The apparatus in this experiment is readily constructed from pieces of $\frac{3}{4}$-in. plywood. Five pairs of objects are cut out having shapes like those shown in Fig. A. With holes drilled through their centers, two pairs of these bodies at a time are bolted with machine screws and wing nuts to a crossbar as shown in Fig. C. The slotted crossbar, made of $\frac{1}{4}$-in. plywood, is symmetrical in shape and, when pivoted by itself, will balance. All five pairs of masses, each with their center bolt and wing nut, are put on a beam balance and weighed. Make a sketch on your data sheet, like the one in Fig. A, and label each one with its mass in grams.

Procedure and Measurements. Select the large and small disk pairs and mount them as far out on the ends of the crossbar as possible. Slide either or both pairs back and forth until balance is acquired, and then measure the distances r_1 and r_2 as shown in Fig. C. Record the masses and their distances in a table of five columns as shown in Table 1. Give the system a push and note that it rotates smoothly about its center of mass.

Now fasten a cord to screw eyes in the ends of the crossbeam and suspend the system from the same pivot peg **P** as shown

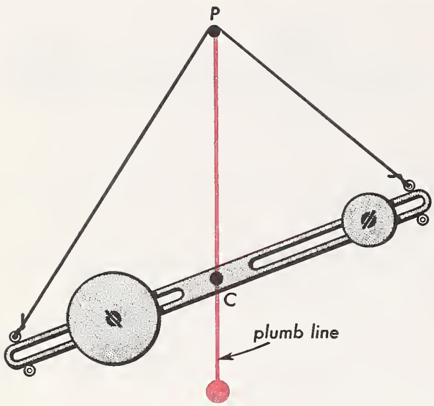
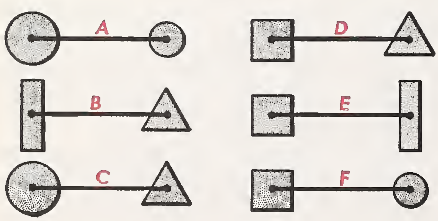


Fig. D. Demonstration that the center of gravity is at the same point as the center of mass.

in Fig. D. Suspend a plumb from the peg ***P***, and the plumb line should cross the center of gravity hole at **C**. This latter part is a check upon the previous balance position and shows that the center of mass and center of gravity are at the same point. Slip the cord along the peg ***P***, orienting the system at a different angle, and note that the plumb line still crosses at **C**.

Repeat this entire procedure for two different mass pairs and record the data in Table 1. Third, fourth, and fifth configurations should be selected, and the procedure repeated. As each set is recorded, make a simple sketch as shown in Fig. E of the bodies selected so that no mistakes will be made in recording the proper masses in Table 1.

Fig. E. Mass configurations for the six different experimental trials.



Data. We will now assume that the experiment has been completed and that the data shown in Table 1 have been recorded.

Table 1. Recorded Data

Configuration	m_1 (gm)	r_1 (cm)	m_2 (gm)	r_2 (cm)
A	426	12.1	210	24.3
B	352	22.1	395	19.6
C	426	18.0	395	19.6
D	454	16.2	395	18.4
E	454	18.4	352	23.5
F	454	11.1	210	24.1

Calculations. To carry out the calculations for this experiment, make a table of three columns as shown by the headings in Table 2. The final values for configuration ***A*** only are given as a guide and for comparison purposes. Complete the table by filling in the columns for the other five configurations. Express your answers to three significant figures only.

Table 2. Calculated Results

Configuration	$m_1 \times r_1$ (gm cm)	$m_2 \times r_2$ (gm cm)
A	5150	5100

By Eq. (2) the so-called ***mass moments*** in the second column should agree with those in the third column. Differences of less than 3% can be expected in this experiment.

Results and Conclusions. In your laboratory report answer the following questions:

1. What is the largest percentage error between mass moments in the six trials of this experiment?
2. Why can we neglect the mass of the crossbar in this experiment?
3. What have you learned about the center of gravity in this experiment?

Mechanics | Lesson 30

HORSEPOWER

Today we are living in the machine age, an era of automation. A great many people who buy a new car are interested in the horsepower of the motor as well as its efficiency, etc. Our laboratory lesson is one involving horsepower, and in performing it we will see one of the many ways one can go about measuring this all-important factor, ***horsepower.***

Theory. Work and potential energy, we have seen in previous lessons, is given by force times distance.

$$\text{work} = F \times s \tag{1}$$

Power is defined as the time rate of doing work and is given by

$$P = \frac{F \times s}{t} \tag{2}$$

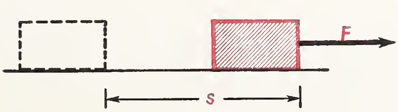
In the mks system of units, force is measured in ***newtons,*** distance in ***meters,*** and power in ***newton meters per second.*** Since 1 newton meter = 1 joule, power is also measured in ***joules per second.***

$$1\ \frac{\text{joule}}{\text{sec}} = 1\ \text{watt} \tag{3}$$

In the English system of units, force is measured in ***pounds,*** distance in ***feet,*** and power in ***foot-pounds per second.*** Furthermore

$$\boxed{1\ \text{hp} = 550\ \frac{\text{ft-lb}}{\text{sec}}} \tag{4}$$

Fig. A. The work done to overcome friction goes into heat energy.



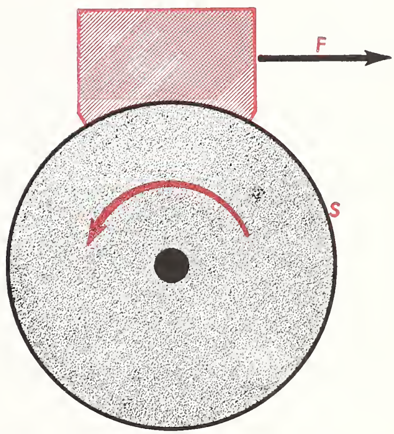


Fig. B. Work done against friction between wheel and block is converted into heat energy.

To introduce the basic principles in this experiment, let us imagine that we slide a block along the table as shown in Fig. A. Because of friction we exert a force F for a distance s and do an amount of work $F \times s$.

Now suppose we change the shape of things and slide a block around a wheel or disk as shown in Fig. B. Or what is equally effective, hold the block still and turn the wheel. For one turn of the wheel the force F has effectively traveled a distance equal to the circumference of the wheel, $s = \pi d$. If the wheel is turned n revolutions, the total distance s will be

$$s = n\pi d \tag{5}$$

and the work done will be

$$\text{work} = Fn\pi d \tag{6}$$

If t is the time it takes to make the n revolutions, the power developed is

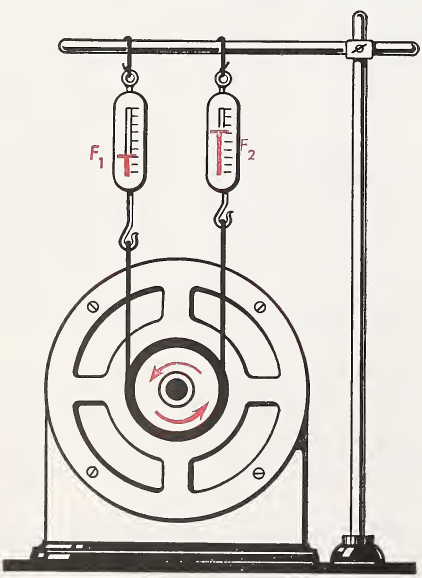
$$\boxed{P = \frac{Fn\pi d}{t}} \tag{7}$$

Object. ***To determine the horsepower of an electric motor.***

Apparatus. The apparatus to be used in this experiment consists of an electric motor with a V-groove pulley mounted on the shaft. The two ends of a heavy cord or leather belt are fastened to spring scales and looped under the pulley as shown in Fig. C. If the motor turns counterclockwise, friction between the belt will increase the belt tension on the left and decrease it on the right. Since these forces oppose each other, F_1 opposing the motion and F_2 aiding the motion, the effective force F, against which the pulley is turning, is given by the difference between the two:

$$\boxed{F = F_1 - F_2} \tag{8}$$

Fig. C. Electric motor with pulley, friction belt, and spring scales for measuring mechanical power.



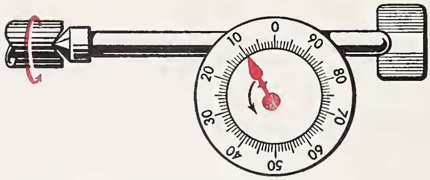


Fig. D. Revolutions counter.

To determine the power developed by the motor as it rotates at constant speed, we must measure the time in seconds required to make a given number of turns. The time can be measured with a stop watch, and the number of turns by a small revolutions counter of the type found in every machine shop (see Fig. D).

When the chisel-pointed end P of the counter spindle K is inserted in the conical center hole on the end of the motor shaft, the dial pointer will make 1 complete turn for every 100 turns of the motor.

Procedure. Set the motor running and tighten the pulley belt until spring F_1 shows a force of 1 to 2 lb more tension than F_2. With the revolutions counter in contact with the motor shaft and turning smoothly, start the watch as the pointer passes the zero mark on the dial, and stop it as it passes the same mark four turns later. While the motor is still turning, note the two spring balance readings. Also measure the belt diameter d where it goes around the pulley.

Make a table of five columns, as shown in Table 1, and record the measurements just made. Then tighten up the belt a little by raising the spring support until the spring balance difference is almost 3 lb, and repeat all measurements. Repeat this operation for about five trials, tightening the belt each time and recording all the measurements.

Data. Assume that we have performed this experiment five times and recorded the data given in Table 1.

Table 1. Recorded Data

Trial	F_1 (lb)	F_2 (lb)	n (turns)	t (sec)
1	2.3	.8	400	8.9
2	4.6	1.1	400	9.3
3	6.8	1.4	400	9.9
4	9.2	1.7	400	11.0
5	11.4	1.9	400	12.3

$d = 1.7$ in.

These data should now be used to calculate the horsepower of the motor under these five different loaded conditions.

Calculations. A table of seven columns should be made for your calculations. Column headings are given in Table 2, along with the calculated results for trial 1. Complete the calculations for the other four trials.

Table 2. Calculated Results

Trial	n/t (rps)	F (lb)	$Fn\pi d$	$\frac{Fn\pi d}{t}$	P (hp)	P (watts)
1	45.0	1.5	267	30.0	.055	41

Results and Conclusions. Draw a graph for the results of this experiment. Plot the values of n/t of column 2 vertically, against values of hp of column 7 horizontally. The divisions on the vertical scale should be marked 0, 10, 20, 30, 40, and 50 rps, while the divisions on the horizontal scale should be 0, 0.05, 0.10, 0.15, 0.20, and 0.25 hp.

What conclusions can you draw from the graph?

Mechanics | Lesson 33

ENERGY AND MOMENTUM

The Problem. Everyone knows that to push a large nail into a block of wood requires a force of hundreds of pounds, and yet, by means of a 1- or 2-lb hammer it is a simple matter to drive it in by a succession of blows. Here is an experiment to see how this comes about. A heavy weight is dropped several times from a height of about one meter so as to drive a large nail into a block of wood. Measurements of mass and distance are made and the principles of energy and momentum are applied to determine the enormous forces involved during impact.

Theory. As shown in Fig. A, a mass M of several kilograms falls a distance h, striking the head of a nail at point B. In coming to rest the mass M exerts a force F, driving the nail head to the point C.

Raised to the point A the mass M has potential energy Mgh, and when it falls freely, this energy is transformed into kinetic energy $\frac{1}{2}Mv^2$. By conservation of energy, Mechanics, Lesson 31, Eq. (6),

$$Mgh = \tfrac{1}{2}Mv^2 \qquad (1)$$

In bringing the mass to rest, this energy is expended as **work done,** exerting a force F and driving the nail a distance s into the wood. We therefore apply the work equation from Mechanics, Lesson 31, Eq. (5), and write

$$\boxed{Fs = Mgh} \qquad (2)$$

During impact we can also apply the prin-

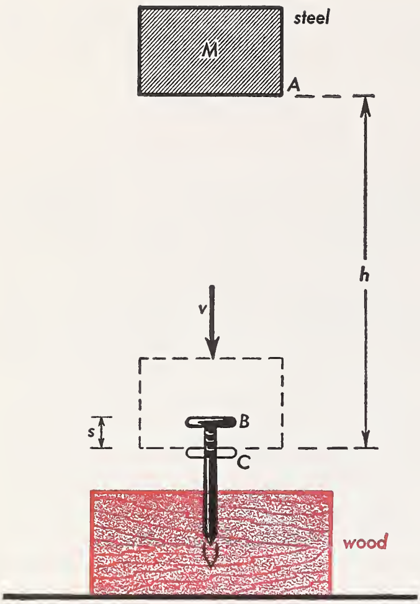


Fig. A. A falling mass *M* drives a nail into a block of wood.

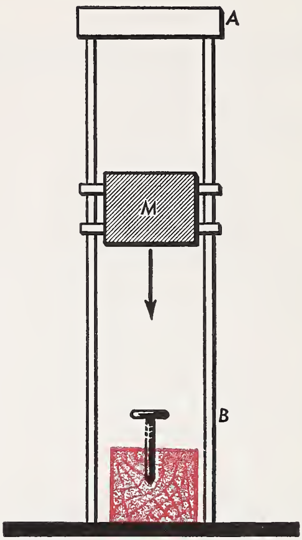


Fig. B. Nail-driving apparatus for laboratory experiment.

ciples of momentum as given by the impulse equation

$$Ft = Mv \tag{3}$$

where F is the average force on the nail and t is the time over which it acts.

Apparatus. A large mass M of several kilograms, with grooves or brackets on two sides, is mounted between two rods as shown in Fig. B. A large nail, or spike, with only its point driven into a block of wood is carefully located at the base of the guide rods so that the falling mass strikes the nail head a direct and centered blow. The mass is raised to the highest point A and released a number of times. With each succeeding blow the nail is driven farther and farther into the wood. Since the frictional resistance between the wood and the nail increases the deeper the nail becomes embedded, the distance the nail is driven with each succeeding blow decreases.

Object. ***To determine the magnitude of the force required to drive a nail into a block of wood.***

Procedure. In order to proceed with the experiment make a drawing like the one shown in Fig. C. This will serve as a guide in recording the proper data as well as in making the final calculations from the measurements. The data should be recorded in a table of two columns as shown in Table 1.

First start the nail in the wood block by means of a hammer, being sure that the nail is vertical when centered between the guide rods. Weigh the mass M and record it in kilograms. Measure the initial distance d from the top of the nail head to the top of the block, and record it in column 1 as the initial length of the nail. Raise M to its highest point A and measure the distance in meters. Now drop the mass M to strike the first blow and record the reduced nail height d as the first reading in the second column.

Raise **M** to the highest point, again drop it to strike the second blow, and record the new nail height **d** in the second column. Repeat this process until the nail is driven all the way into the block of wood and the top of the head is flush with the surface.

Measurements and Data. Suppose that the measurements in this experiment have been properly made and that they have the values recorded in Table 1. We may now proceed to make all our calculations from these data.

Table 1. Recorded Data

Initial Measurements	d (m)
$M = 5.2$ kg	.082
	.061
$d = .120$ m	.048
$l = 1.03$ m	.032
	.022
	.013
	.005
	0

Calculations. Proceed by making a table of six columns with headings like those shown in Table 2. The first row of calculations has been completed to serve as your guide for computing the others.

Table 2. Calculated Results

s (m)	h (m)	Mgh (joules)	F (newtons)	F (lb)	k (m)
.038	.948	48.3	1270	284	.038

The values in column 1 are obtained by taking the differences between successive values of **d** (see Fig. C). The values of **h** are found by subtracting each value of **d** in Table 1, column 2, from the fixed height **l**. The values of **F** in column 4 are obtained by use

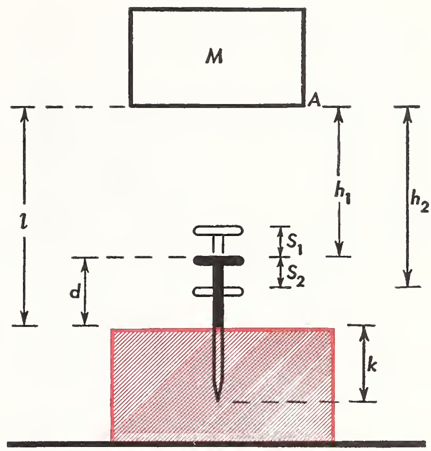


Fig. C. Dimension diagram showing all measurable quantities needed in this experiment.

of Eq. (2), that is, by dividing the values **Mgh** in column 3 by the values of **s** in column 1. Since

$$1 \text{ newton} = 0.224 \text{ lb}$$

the values of **F** in lb are obtained by multiplying column 4 by 0.224. Finally, the values of **k** are obtained by subtracting each value of **d** in column 2 of Table 1 from the initial length of the nail.

Results. Note from your calculated results in columns 4 and 5 the large forces exerted. Even though the mass **M** has a weight of a little over 10 lb, it can exert forces of hundreds and even thousands of pounds on impact. This clearly explains why it is that a 1- or 2-lb hammer is able to exert the large forces needed to drive a nail into wood.

Conclusions. Interesting conclusions can be drawn from this experiment by plotting a graph of the calculated results in columns 4 and 6 of Table 2. Plot such a graph for your data and compare it with the one shown in Fig. D. (The graph in Fig. D is

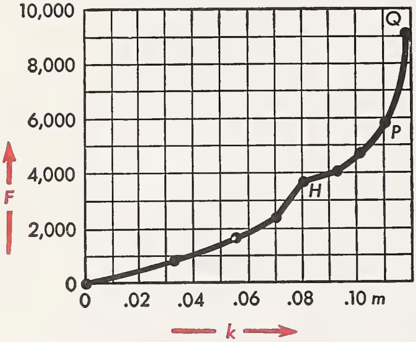


Fig. D. Graph of the force impulses exerted in driving a certain nail into a block of pine wood.

drawn for a different nail and block of wood than the one recorded in Tables 1 and 2.) It shows, as your graph should, that as the nail is driven farther and farther into the wood, the force F increases.

Not only does the friction between the wood and metal increase because of increased contact area but also new wood must be penetrated with each blow. When a region of hard wood, like a knot, is encountered, the nail is not driven in so far, the impact time is shorter, and the force is increased. Such a region is indicated by the bump at H in Fig. D. Soft regions produce the opposite effects. The sudden rise near the end, P to Q, is due to the larger force needed to sink the nail head into the wood.

Briefly explain the meaning of any irregularities in your graph. If time permits, make use of your recorded data, calculations, and Eqs. (1) and (3), and compute the impulse time for each blow of the mass M in this experiment. For these calculations make a third table of four columns having the following headings: $2gh$, v, Mv, and t respectively.

***Mechanics* | Lesson 35**

LEVERS

This is a laboratory experiment on the principles of levers. In it we find a great similarity to an earlier experiment on the equilibrium of rigid bodies.

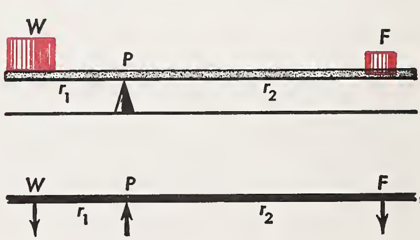
Theory. The theory of levers is relatively simple and is based upon what are called ***force moments,*** or ***mass moments.*** In Fig. A we see a line diagram of a lever of the first class along with a force diagram below.

To lift the heavy load W at a distance r_1 from the pivot P, a smaller force F is applied at a distance r_2 from the pivot. Now we apply the principles of the lever.

$$\boxed{W \times r_1 = F \times r_2} \qquad (1)$$

These products $W \times r_1$ and $F \times r_2$ are called ***force moments,*** and are simply counterclockwise and clockwise torques, respectively, acting on the rigid body, the lever. Since in performing this experiment we are going to use weights that are specified in

Fig. A. Diagrams of a first-class lever.



gram mass, we can express W and F of Eq. (1) as m_1g and m_2g, respectively.

$$m_1g \times r_1 = m_2g \times r_2$$

If we now cancel the g's, we obtain

$$\boxed{m_1r_1 = m_2r_2} \qquad (2)$$

These products, m_1r_1 and m_2r_2, are called ***mass moments,*** and we recognize the relation as one locating the center of mass.

The primary function of a lever is to produce a large force W at the expense of a smaller force F. A lever, then, is a kind of mechanical magnifier that has what is called a ***mechanical advantage.*** The mechanical advantage of any lever is given by the relation

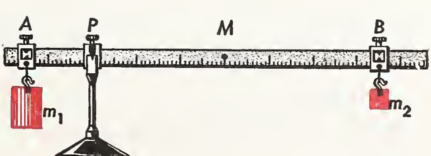
$$\text{M.A.} = \frac{W}{F} \qquad (3)$$

If the load lifted is 100 lb and the applied force is 20 lb, the mechanical advantage is 100/20, or 5, the latter signifying that one can lift a load five times that of the applied force.

In Mechanics, Lesson 34, we saw how all levers may be classified as first-, second-, or third-class levers, all depending upon the relative positions of the pivot with respect to the load and the applied force. The principles are the same in all and are given by Eqs. (1) and (2).

Apparatus. We are going to set up first-, second-, and third-class lever systems and determine the mass moments involved with each. The apparatus to be used is shown in Fig. B, and consists of a meter stick with a movable pivot support, and several hooks that can be moved along the stick. A clamp stand and pulley, as well as a platform balance and a set of metric weights are needed, as shown in Fig. C.

Fig. B. Apparatus for first-class lever experiment.



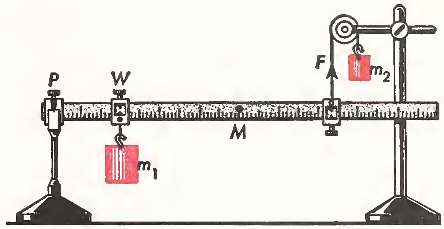


Fig. C. Apparatus for second-class lever experiment.

Object. *To test the law of moments as it applies to levers of all classes.*

Procedure and Measurements. Remove all hooks from the meter stick and weigh it on the platform balance. Weigh one of the several identical hooks and record the mass in grams. For example, meter-stick mass = 200 gm, hook mass = 38.0 gm. Mount the meter stick on the pivot stand with the pivot P at the center point M, that is, the 50-cm mark. Suspend a 1000-gm mass from a hook at the 35-cm mark, and a mass of 300 gm from a hook on the other end of the meter stick. Slide this smaller mass along until balance is attained, and record the data by making a line drawing as shown in Fig. E. Be sure to include the mass of each hook in recording m_1 and m_2.

Repeat the experiment by moving the 1000-gm mass to the 25-cm mark and use a 500-gm mass for the applied force. Record the data by making another line drawing as shown in Fig. E.

Move the pivot P to the 15-cm mark, the load W to the 3-cm mark, and with a mass of 100 gm for the applied force, locate the balance point as before. Record the data as illustrated by the third diagram in Fig. E.

For a first trial with a second-class lever move the pivot to the 3-cm mark of the meter stick, the load ***W*** to the 15-cm mark, and apply the upward force ***F*** with a clamp stand and pulley and a 300-gm mass as shown in Fig. C.

Slide the ***F*** hook along until balance is acquired and record the data as indicated by the fourth diagram in Fig. E. Note that the weight of the hook at ***F*** is down, while the force due to the 300-gm mass is up. The total upward force ***F*** is represented by the mass difference 300 − 38, or 262 gm.

Move the load ***W*** to the 20-cm mark, increase the other mass to 350 gm and find balance. Record the data as before.

For one trial with a third-class lever the meter stick should be pivoted at its center point by drilling a hole through the center at the 50-cm mark and slipping it over a steel pin held in a clamp stand (see Fig. D). A 300-gm load should then be placed at the 95-cm mark, and an upward force ***F*** applied with a 1000-gm mass and pulley as shown. Record the data in a line diagram as shown at the bottom of Fig. E.

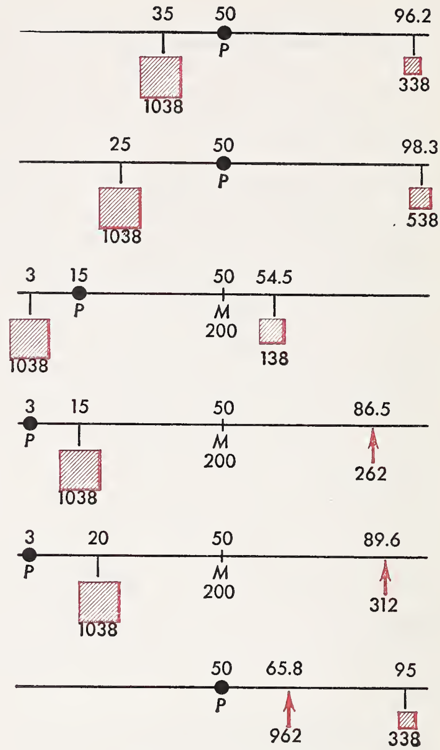


Fig. E. Recorded data.

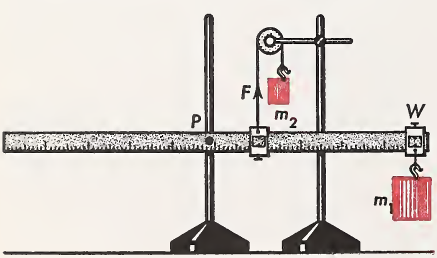
Calculations and Results. Your calculations can best be made by recording in a table of four columns. Use headings as shown in Table 1, and be sure to include the mass moment due to the mass of the meter stick itself when the pivot ***P*** is not located in the center at ***M***. An indication of how carefully the measurements were made will be shown by how nearly the values in column 2 are like those in column 3.

Table 1. Calculated Results

Lever Class	Counter-clockwise Moments	Clockwise Moments	M.A.
1	15570	15620	3.07

Calculated values for trial 1 are already recorded in Table 1 to serve as a guide in computing the others. Carry mass-moment calculations to four significant figures only.

Fig. D. Apparatus for third-class lever.



Conclusions. Make a brief statement of what you have learned from this experiment.

Mechanics | Lesson 38

BALLISTICS

The term ***ballistics*** is applied to the science of hurling missile weapons from a gun or launching device. One of the major problems in this science is concerned with the determination of the muzzle velocity of shells as they leave the end of the gun barrel. In the experiment described here we are going to fire various kinds of cartridges from a 22-caliber rifle and measure the muzzle velocity of the bullets.

Theory. In a previous lesson we saw how the ***law of conservation of momentum*** is applied to problems of this kind. Simplified diagrams of the barrel of a gun and the exploding charge as it exerts equal but opposite forces on the bullet and shell housing, respectively, are shown in Fig. A.

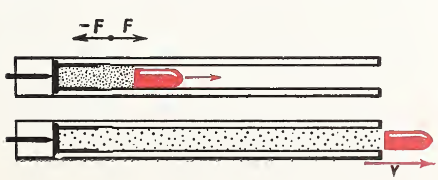
Since the action force F on the bullet is at all times equal and opposite to the reaction force $-F$ on the shell and gun, we can apply the impulse equation to both

$$Ft = mv \tag{1}$$

In general, the bullet will leave the gun barrel with a momentum mv, and the gun will recoil with an equal but opposite momentum $m'v'$.

Apparatus. Of the many methods that have been employed for determining the muzzle velocity of shells from guns we will use the one shown in Fig. B. A 22-caliber rifle is clamped tightly with its barrel pointing straight upward and the stock resting against the floor. A small tubular fitting over the top end of the barrel is used to support a cylindrical block of wood.*

Fig. A. Diagram of a rifle bullet being fired from a gun barrel.



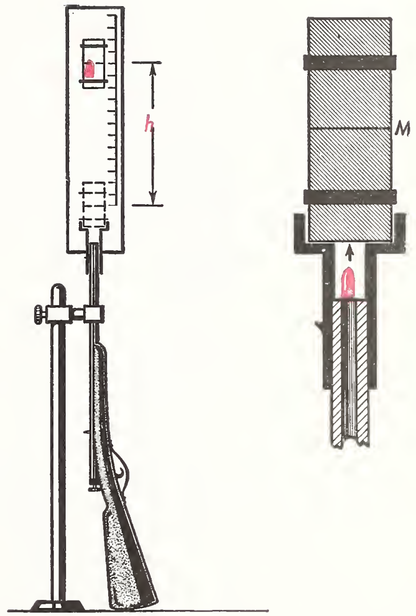


Fig. B. Rifle arrangement with attachments for ballistics experiment.

As the bullet leaves the gun barrel, it becomes embedded in the wood block, and the two are carried upward to a height h as shown. Since this is an impact or collision problem, we can apply the ***law of conservation of momentum*** from a previous

* Hard wood about 2 in. in diameter and 4.5 in. high, with two tightly fitted metal bands to prevent splitting, are quite suitable. The same block can be used for several firings.

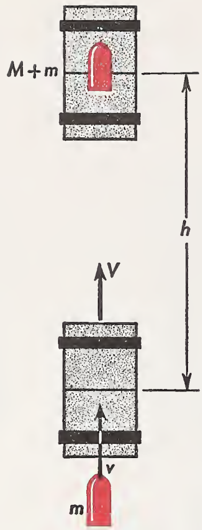


Fig. C. Shows measurable quantities in the ballistics experiment.

lesson: ***the total momentum before impact equals the total momentum after impact.***

With the wood block initially at rest, the total momentum before impact is just that of the bullet, mv. See Fig. C. After impact the bullet and block, with a total mass $M + m$, recoil upward with a velocity V and total momentum $(M + m)V$.

Therefore, we can write

$$mv = (M + m)V \tag{2}$$

Since v is the unknown, transpose m and obtain

$$\boxed{v = \frac{M + m}{m} V} \tag{3}$$

To find the recoil velocity V, we measure the height h to which the block rises, and apply the law of freely falling bodies. See Mechanics, Lesson 10.

$$\boxed{V = \sqrt{2gh}} \tag{4}$$

Typical cartridges known as *22-short, 22-long,* and *22-high-velocity* are convenient for our use. These, as shown in Fig. D, are combinations of two shell and charge sizes, and two lead bullet sizes.

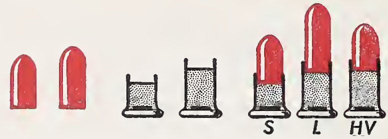


Fig. D. Bullets, shells, and assembled cartridges for a 22-rifle.

Object. ***To determine the muzzle velocity of a rifle bullet.***

Procedure. For safety reasons this part of the experiment should be performed by the instructor. First, remove the bullets from one each of the three types of shell. Weigh the bullets and record their mass m in kilograms. See Table 1. Weigh the wood block and record its mass M in kilograms.

Insert a 22-short cartridge in the gun and place the block of wood in the support at the end of the gun barrel. Stand back so you can see the scale clearly, and as the instructor fires the gun, note the maximum height to which the block rises. A black band around the center of the block helps in making this observation. Record the height h in meters.

Repeat the experiment with the other two cartridge types, being sure to note the proper mass M of the wood block. If the same block is used several times, its mass will increase each time it is fired. If time permits, repeat the experiment once for each shell type and record.

Measurements and Data. Let us assume that you have performed the experiment and recorded the data for six trials as shown in Table 1.

Calculations and Results. To complete this experiment, the muzzle velocities must be calculated and a final report written.

Table 1. Recorded Data

Trial	Shell Desig.	m (kg)	M (kg)	h (m)
1	22-short	.0018	.224	.58
2	22-long	.0026	.226	1.30
3	22-HV	.0018	.229	.82
4	22-short	.0018	.231	.56
5	22-long	.0026	.234	1.18
6	22-HV	.0018	.236	.78

For this purpose make a table of six columns with headings as shown in Table 2. Using Eq. (4), calculate the recoil velocity **V** of the block for each trial, and with Eq. (3) find the corresponding muzzle velocities **v**. Finally, calculate the bullet momentum ***mv***. The computed values for the first trial are given as your guide in making the necessary calculations.

Conclusions. Answer the following questions in your final report:

1. Which of the three cartridges gives the highest muzzle velocity?
2. Which of the three cartridges gives the highest momentum?
3. Why do we apply conservation of momentum at impact of the bullet with the wood block and not conservation of energy?

Table 2. Calculated Results

Shell Desig.	$M + m$ (kg)	$\frac{M + m}{m}$	V (m/sec)	v (m/sec)	mv (kg m/sec)
22-short	.226	126	3.37	424	.76

***Mechanics* | Lesson 40**

CENTRIPETAL FORCE

Every object that moves in a circular path about some center has exerted upon it an unbalanced force called the centripetal force. It is the purpose of this experiment to measure this force and to see how it depends upon the speed of rotation.

Theory. In Mechanics, Lesson 39, we saw how angles in rotational motion are measured in radians. In these angular units there are 2π, or 6.28, radians in one complete circle.

$$2\pi \text{ radians} = 360°$$

If an object moves around a circle of radius r, the angle turned through (see Fig. A) is given by

$$\theta = \frac{s}{r} \qquad (1)$$

where s is the distance measured along the circle and θ is the angle in radians. See Eq. (3), Mechanics, Lesson 39.

Transposing Eq. (1), we obtain

$$s = r\theta \qquad (2)$$

If a body moves with uniform speed v, as shown in Fig. B, we have

$$v = \frac{s}{t} \qquad (3)$$

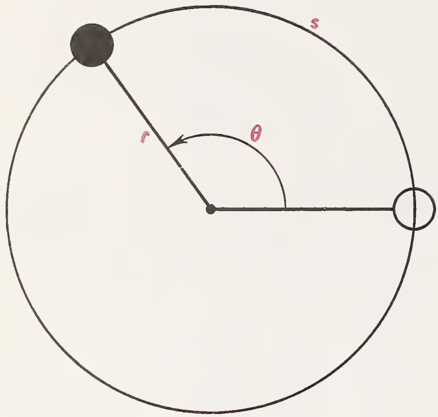


Fig. A. In mechanics angles are measured in radians.

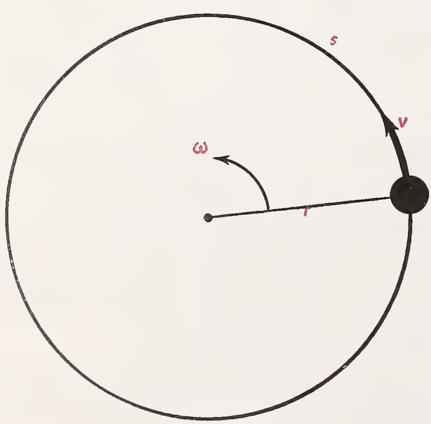
and, in terms of angular velocity ω,

$$\omega = \frac{\theta}{t} \tag{4}$$

If an object makes n revolutions, the total angle θ turned through is $2\pi n$. Substituting $2\pi n$ for the angle θ in Eq. (4), we obtain for the angular velocity ω the relation

$$\boxed{\omega = \frac{2\pi n}{t}} \tag{5}$$

Fig. B. Speed and distance along the circle are related to the radius and the angular velocity.



Now if we take Eq. (3) and substitute for s the value $r\theta$ given by Eq. (2), we obtain

$$v = \frac{r\theta}{t} \tag{6}$$

Since Eq. (4) shows that θ/t is equal to ω, we can substitute ω for θ/t in Eq. (6) and obtain

$$v = r\omega \tag{7}$$

Centripetal force, as presented in the preceding lesson, is given by

$$F = m\frac{v^2}{r} \tag{8}$$

If we now square both sides of Eq. (7) and substitute $r^2\omega^2$ for v^2 in Eq. (8), we obtain

$$F = m\frac{r^2\omega^2}{r}$$

or finally,

$$\boxed{F = mr\omega^2} \tag{9}$$

Equations (8) and (9) are the most useful forms for calculating centripetal force F.

Apparatus. A special piece of equipment is used in this experiment, and a cross-section diagram of the principal parts is shown in Fig. C. It consists of a rectangular metal frame within which is located a cylindrical mass m attached to a coil spring S. A shaft mounted with its axis AA' passing through the center of mass of the entire assembly is connected to an electrically driven variable speed rotator (not shown).

When the entire frame is set rotating, the mass m moves outward from T to Q, extending the spring as shown. By increasing or decreasing the speed of rotation the spring extension changes and the mass m can be adjusted to an exact position by watching a pointer P and index I. This pointer is a lever L loosely pivoted at O, and so shaped that when the mass m presses against it at N, its tip end P moves up a distance of about 5 mm.

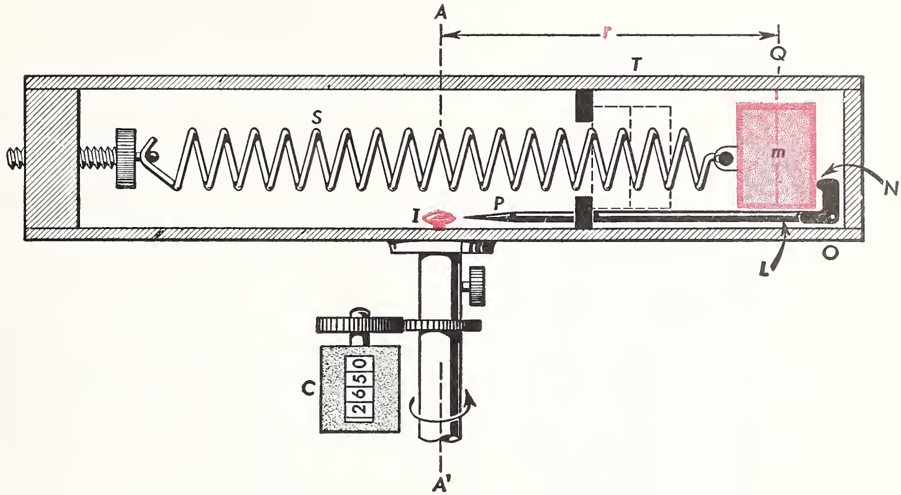


Fig. C. Apparatus for measuring centripetal force.

The frequency of revolution is determined by means of a revolution counter **C** geared directly to the shaft. When the proper speed is acquired, a stop watch is used to measure the time for one hundred or more revolutions of the frame.

Object. To measure the centripetal force required to keep a known mass moving in a circle with constant speed.

Measurements. The centripetal force frame, as shown in Fig. C, is set into rotation and the speed varied until the pointer **P** lines up with the index ***I***. Look now to the revolution counter, and as the numbers pass any even hundred, start the stop watch. Stop the watch at the end of the next hundred turns and record the readings under ***n*** and ***t*** as shown in Table 1.

Remove the force frame from the rotator and suspend it from a clamp stand as shown in Fig. D. Attach a weight holder to the mass ***m*** and then add weights until the pointer **P** is again centered on the index ***I***. Record the mass ***M*** in kg in column 2, and below the table the mass ***m***. The latter is usually stamped somewhere on the metal cylinder itself.

With a pair of dividers span the distance ***r*** between the axis of rotation ***AA'*** (indicated by a scribe line on the frame) and the center of mass of the cylinder (indicated by a line around its center). Measure this distance ***r*** with a ruler and record the distance below the table as shown.

The total downward force on the spring, due to both the masses ***M*** and ***m***, is equal to the centripetal force exerted on ***m*** when the frame is in rotation. By Newton's Second Law of Motion ($F = ma$), we can write

$$F = (M + m)g \tag{10}$$

This equation should be recorded below the table.

For a second trial change the tension in the spring. This is accomplished by turning the threaded nut **N**. Repeat all adjustments and record the measurements as trial 2. If time permits, change the spring tension again and make one or two more trials and record.

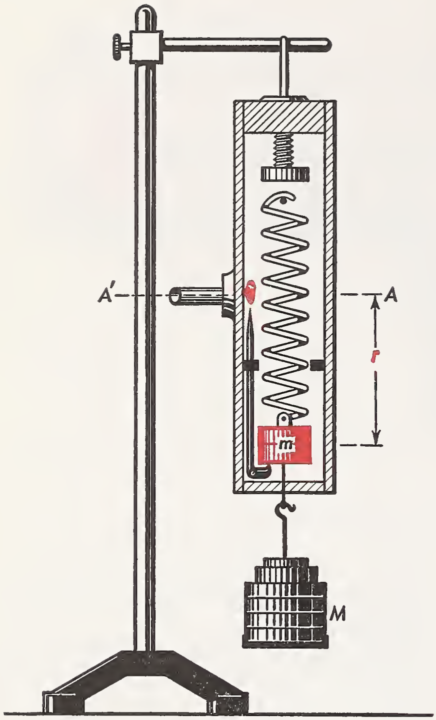


Fig. D. Centripetal force apparatus.

Data. If you have recorded the data, the various readings you will have written down will look like those given in Table 1.

Calculations. With the data recorded in Table 1, the calculations to be made are best carried out and tabulated under the headings shown in Table 2.

The first row of calculations are already completed, and may be used as a guide for

Table 1. Recorded Data

Trial	M (kg)	n (turns)	t (sec)
1	2.60	100	11.4
2	2.70	200	22.3
3	2.90	200	21.6
4	3.10	300	31.5

$m = 0.1527$ kg; $r = 0.058$ m

the other trials. Column 2 is calculated from the data recorded in columns 3 and 4 in Table 1. The angular velocity ω is next found by use of Eq. (5). Column 5 is calculated by using Eq. (9), and column 6 by using Eq. (10).

Results. Column 5 of Table 2 gives the centripetal force obtained by spinning the apparatus, while column 6 gives the gravitational force required to stretch the spring the same amount. These two forces should be equal in magnitude, and any differences between the values in the last two columns may be ascribed to experimental error.

Include a graph in your final report, plotting ω^2 vertically against F horizontally. Make the vertical scale eight squares high and label them 0, 500, 1000, . . . 4000 rad/sec. Make the horizontal scale seven squares wide and label them 0, 5, 10, 15, . . . 35 newtons.

Conclusions. Make a brief statement in your final report of what you have learned from this experiment.

Table 2. Calculated Results

Trial	n/t (rps)	ω (rad/sec)	ω^2 (rad/sec)^2	$mr\omega^2$ (newtons)	F (newtons)
1	8.77	55.0	3020	26.8	26.9

Mechanics | Lesson 43

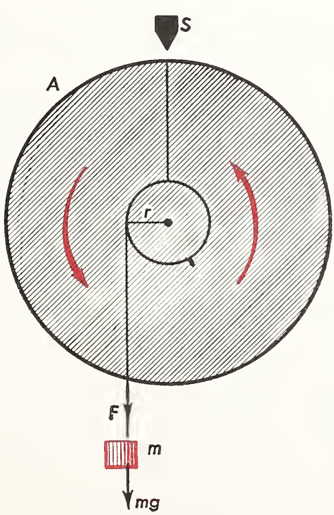
MOMENT OF INERTIA

Our last experiment in mechanics is concerned with the determination of the moment of inertia of several regularly shaped bodies. These bodies are readily made from $\frac{3}{4}$-in. plywood and take the form of a ring, a disk, and a rectangle.

Theory. We begin with a large disk of $\frac{1}{4}$-in. plywood about 60 cm in diameter, with a smaller disk of $\frac{3}{4}$-in. plywood glued tightly to it as shown in Fig. A. As a wheel and axle this basic turntable is mounted on the front hub of a bicycle wheel and fastened to the wall so it is free to turn about a horizontal axis. A cord wrapped around the axle several times has one end looped over a small wire nail to keep it from slipping and the other end fastened to a small weight of mass **m**. (*Note:* The smaller disk or axle should be on the back face of the disk, thereby leaving the front face clear for mounting objects.) The rotational counterpart of the force equation in linear motion is the ***torque equation***

$$L = I\alpha \tag{1}$$

Fig. A. Turntable apparatus for experiment on moment of inertia.



In this experiment we will determine by measurement the values of the torque **L** and the angular acceleration α, and calculate the moment of inertia I. Transposing Eq. (1), we have

$$\boxed{I = \frac{L}{\alpha}} \tag{2}$$

The torque **L** acting on the turntable is given by

$$L = F \times r$$

where in Fig. A it can be seen that

$$F = mg$$

Consequently we will use the relation that

$$\boxed{L = mgr} \tag{3}$$

To find the angular acceleration α we use the angular formula for acceleration, which is the counterpart of the linear equation.

$$\theta = \tfrac{1}{2}\alpha t^2 \tag{4}$$

Solving for α, we obtain

$$\boxed{\alpha = \frac{2\theta}{t^2}} \tag{5}$$

Now we are going to measure θ and **t** to find α, and measure **m** and **r** to find the torque **L**. These, substituted in Eq. (2), will give us the moment of inertia I.

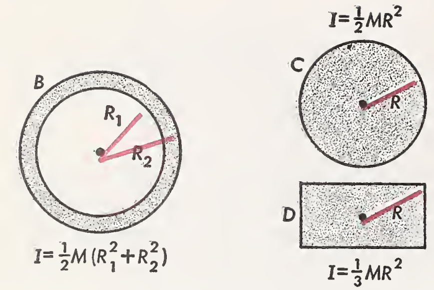


Fig. B. Diagrams of objects used in this experiment on moment of inertia.

Object. *The object of this experiment is to determine the moment of inertia of several regularly shaped bodies.*

Apparatus. Besides the wheel and axle shown in Fig. A we will use three objects having the shapes shown in Fig. B. The first is a uniform ring ***B***, the second a disk ***C***, and the third a rectangle ***D***. A set of weights, a beam balance, and a stop watch, or clock, are needed for weighing and measuring time.

Procedure and Measurements. The first step is to wrap the cord around the axle several times, hang a 40-gm mass from the end of the cord, and turn the disk so the line drawn on it lines up with the starting marker ***S***. As the wheel is released and starts from rest, start the watch. After three complete turns of the wheel, stop the watch. Repeat this timing process several times and take the average time. Next measure the radius ***r*** for the axle. Record your readings in a table of eight columns with headings like those shown in Table 1.

For the second trial weigh object ***B*** and record its mass ***M***. Measure the inside and outside diameters and record under ***D*** in Table 1. Mount the ring on the wheel and axle with two small screws, being careful to center it well so the entire system will balance and rotate smoothly. Now wrap the cord around the axle, attach a small mass of 60 gm to the cord, and again determine the time for this system to make three complete turns. Record the data as illustrated in row two of Table 1.

Weigh the disk ***C*** and measure its diameter. Remove the ring from the wheel and axle, and attach the disk. Wrap the cord around the axle, again attach a 60-gm mass, and measure the time for three complete turns.

Repeat this procedure for the rectangular block and record the data.

Data. Let us assume that we have recorded the data as shown in Table 1, and proceed to make calculations.

Calculations. Your calculations can be conveniently recorded in a table of eight columns as shown in Table 2.

The calculations for objects ***A*** and ***B*** are already given and will serve as a guide and check upon your method. Although the last column is not filled in for ***A***, computations

Table 1. Recorded Data

Object	*D* (m)	*R* (m)	*M* (kg)	*m* (kg)	*r* (m)	*θ* (rev)	*t* (sec)
A	—	—	—	.040	.068	3	7.3
B	.420 .510	.210 .255	.925	.060	.068	3	9.1
C	.384	.192	1.220	.060	.068	3	7.5
D	.548	.274	1.180	.060	.068	3	8.0

Table 2. Calculated Results

Object	mg (newtons)	L (newton m)	2θ (rad)	t^2 $(\text{sec})^2$	α (rad/sec)	I (meas.)	I (theory)
A	.392	.0267	37.7	53.3	.708	.0377	—
B	.588	.0400	37.7	82.8	.455	.0503	.0508

using the theoretical formulas should be made and filled in for **C** and **D**. For this purpose use the formulas shown in Fig. B. Calculations for all other columns are made by using Eqs. (3), (5), and (2) in that order.

Remember that when each of the objects **B**, **C**, and **D** is mounted on the turntable, the measurements of m, θ, and t are for the entire rotating system. Therefore, when the value of I is first calculated, the moment of inertia $I = 0.0377$ kg m^2 must be subtracted from it to find the I (meas.) and recorded in column 7. A comparison of I (meas.) with I (theory) for each of the bodies **B**, **C**, and **D** will indicate the magnitude of any experimental errors.

Results and Conclusions. Make a brief statement of what you have learned in this experiment.

PROPERTIES OF MATTER

HOOKE'S LAW

This is a laboratory experiment on the elasticity of steel. In it we are going to apply Hooke's law to the stretching of a steel wire and, from the measurements, determine a constant called ***Young's modulus.***

Theory. The principles involved in this experiment and the formulas we will use come directly from the preceding lesson on elasticity. A long thin wire is suspended from a rigid support, and a mass m is applied to the lower end to stretch it as shown at the left in Fig. A.

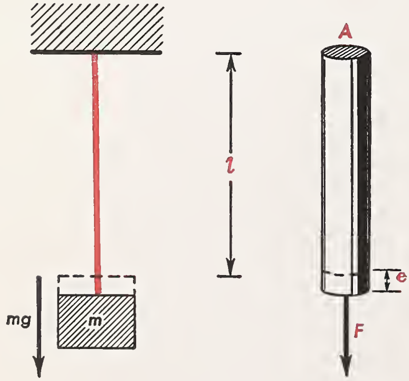
We introduce again the two quantities, called ***stress*** and ***strain***, by the following relations:

$$\text{stress} = \frac{F}{A}$$

$$\text{strain} = \frac{e}{l}$$

F is the force applied to stretch the wire and is equal to mg.

Fig. A. Stress and strain factors in the stretching of a wire.



$$\boxed{F = mg} \qquad (1)$$

A is the cross-sectional area of the wire, and is shown exaggerated at the right in Fig. A. The original length of the wire is given by l, and the elongation or amount of stretch is given by e. The ratio of stress divided by strain is called Young's modulus Y.

$$Y = \frac{\frac{F}{A}}{\frac{e}{l}}$$

Inverting the denominator and multiplying, we obtain

$$\boxed{Y = \frac{Fl}{Ae}} \qquad (2)$$

By measuring the four quantities F, l, A, and e, the elastic constant Y can be calculated.

Apparatus. A thin steel wire, called piano wire, about one meter long is suspended from a rigid support as shown in Fig. B. The crossbar at the top must be several inches thick to reduce bending to a minimum. The wire is twisted tightly around a metal rod P, with the rod resting on a metal plate S.

The lower end of the wire contains a tightly twisted loop fitted around the hook of a 1-kg weight holder. As 500-gm weights are added to the load, one after the other, the wire will stretch by very small amounts. To measure this elongation accurately, a mechanical lever system shown in Fig. C is used. This latter is but one of many methods that have been devised for such purposes.

A small collar C with a setscrew is

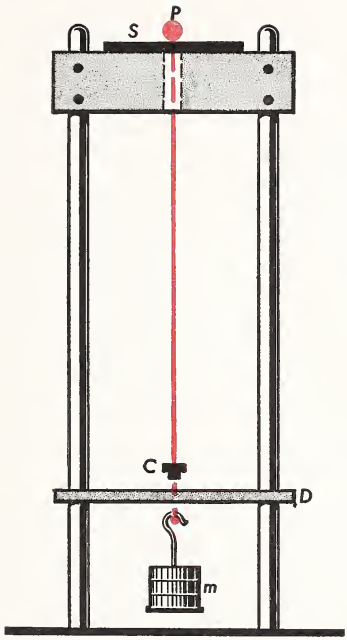
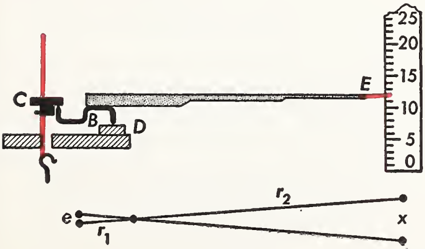


Fig. B. Standard support for Young's modulus experiment.

clamped tightly to the wire a few centimeters above the lower end. A small wire bracket ***B***, fastened to a thin narrow strip of balsa wood about one meter long, serves as a lever. The metal tip of the bracket ***B*** rests under the collar **C**, and the knife edge rests on top of a rigid crossbar support ***D***. When the wire stretches and the collar moves down

Fig. C. Lever system for measuring the elongation of the wire *W*.



ever so little the pointer tip moves up by easily observed amounts as seen on the meter stick ***E***.

A line diagram of the lever action, given at the bottom in Fig. C, shows how to calculate the collar displacement **e** in terms of the lever dimensions and the displacement ***x*** measured on the meter stick. Calling r_1 and r_2 the lever arms, we have by direct proportion

$$\frac{e}{r_1} = \frac{x}{r_2}$$

giving,

$$\boxed{e = x\frac{r_1}{r_2}} \qquad (3)$$

Object. ***To establish Hooke's law and determine Young's modulus for steel by means of a wire.***

Procedure and Measurements. With the 1-kg hooked weight hanging from the lower end of the wire, measure the distance from the top of plate **S** to the top of the collar **C**. This distance should be recorded in cm for ***l***, the length of the wire.

Second, by means of a micrometer caliper, measure the diameter of the steel wire and record as ***d***.

Third, measure the lengths of the two lever arms and record as r_1 and r_2, respectively.

Fourth, make a table of two columns with headings as shown in Table 1 and proceed as follows. With the lever in place, note and record the position **s** of the pointer on the meter stick, and record zero for the corresponding ***m***. Add 500 gm to the load and record the new pointer position **s**. Continue to add 500-gm weights one after the other and record the pointer position **s** with each one in turn. Take your last reading when a total of 5 kg has been added.

Data. Suppose the measurements just described have all been made, and the data

in Table 1 have been recorded. All measurements and calculations are in cgs units.

$$l = 126.4 \text{ cm}$$
$$d = 0.0320 \text{ cm}$$
$$r_1 = 2.9 \text{ cm}$$
$$r_2 = 92.5 \text{ cm}$$

Table 1. Recorded Data

m (gm)	*s* (cm)
0	10.0
500	11.25
1000	12.45
1500	13.70
2000	14.90
2500	16.15
3000	17.40
3500	18.60
4000	19.85
4500	21.10
5000	22.30

We will proceed to use these data for our calculations.

Calculations. Make a table of three columns as shown in Table 2 and determine

Table 2. Calculations

x (cm)	e (cm)	*F* (dynes)
0	0	0
1.25	.0390	4.9×10^5

e and ***F*** for all readings. The first two rows have been filled in to serve as your guide in completing the calculations.

When you have completed the table, plot a graph from the values in the last two columns. Make your graph 8 cm high for the **e** scale and 10 cm wide for the ***F*** scale. Plot the points very carefully and draw your graph line carefully through the points.

Determine from your graph the value of **e** for a force ***F*** of 50×10^5 dynes. Substitute this value of **e** and ***F*** in Eq. (2), along with your calculated cross-sectional area ***A*** and wire length ***l***, and compute the value of **Y**. While there are other ways of using these data to calculate **Y**, the method described here is quite acceptable.

Results and Conclusions. The accepted value of Young's modulus for steel is 19.0×10^{11} dynes/cm^2. Assuming this to be the correct value for the steel wire used in this experiment, calculate the percentage error of your final calculated value. To do this, use the following procedure: Take the difference between your experimental value and the accepted value, divide by the accepted value, and multiply by one hundred. Symbolically

$$\frac{\text{acc. value} - \text{exp. value}}{\text{acc. value}} \times 100 = \text{percent error}$$

Your final report should include an answer to the following question: What conclusion can you draw from your graph?

Properties of Matter | Lesson 5

PRESSURE IN LIQUIDS

The purpose of this experiment is to measure the pressure at different depths within a vessel of water.

Theory. You will remember from our previous lesson on liquid pressure that

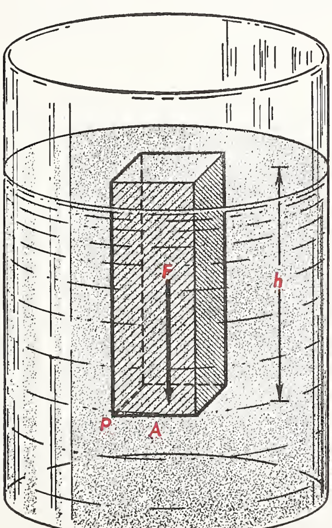
$$\boxed{p = \frac{F}{A}} \qquad (1)$$

and that the force on any given area is given by

$$F = pA \qquad (2)$$

Furthermore, the total downward force on any given area like that shown in Fig. A is given by the weight of the column of fluid above it. To find the weight of a column of liquid it is convenient to know the liquid ***density*** or ***weight density***.

Fig. A. Pressure within a liquid increases with depth.



The density of any given substance or body of matter is given by the ***mass per unit volume***. To find the density one determines the volume of a given mass of the substance and divides one by the other.

$$\text{density} = \frac{\text{mass}}{\text{volume}}$$

In algebraic symbols

$$\boxed{\rho = \frac{M}{V}} \qquad (3)$$

where the Greek letter ρ stands for density.

In the English system of units it is common to find the weight of a given substance, rather than its mass, and to determine what is called its ***weight density***. Weight density is defined as the weight per unit volume and is given by

$$\text{weight density} = \frac{\text{weight}}{\text{volume}}$$

which in algebraic symbols can be written

$$\boxed{\rho_w = \frac{W}{V}} \qquad (4)$$

The densities and weight densities of a few common materials are given in Table 1.

The mass of any column of liquid is given by Eq. (3). Transposing this equation, we obtain

$$M = \rho V \qquad (5)$$

To find the weight of any mass M we multiply by g the acceleration due to gravity. The weight, then, is the total downward force F of a liquid column, and we can write

$$F = Mg \qquad (6)$$

and then

$$F = \rho V g$$

Table 1. Densities and Weight-Densities of a Few Common Materials

Material	ρ (gm/cm^3)	ρ_w (lb/ft^3)
alcohol	.79	49.3
benzine	.70	43.7
blood	1.04	65.0
gasoline	.69	41.2
mercury	13.6	849
olive oil	.918	57.3
water	1.000	62.4
aluminum	2.7	169
copper	8.9	556
gold	19.3	1205
iron	7.9	493
lead	11.4	712

The volume V of a column of liquid (see Fig. A) is given by

$$V = hA \tag{7}$$

so that, upon substitution in Eq. (6), we have

$$F = \rho hAg \tag{8}$$

By direct substitution of ρhAg for F in Eq. (1), we obtain our final equation.

$$p = \frac{\rho hAg}{A} \tag{9}$$

or

$$\boxed{p = h\rho g} \tag{10}$$

Apparatus. The apparatus to be used in this experiment consists of a hollow glass tube about 60 cm long and 4.0 cm outside diameter and open at both ends. See Fig. B. About 150 gm of lead shot are dropped into the bottom of the tube, and some melted paraffin is poured over the shot to hold it in place.

The tube is placed with the weighted end down in a tall cylinder containing water, and we are ready to proceed with measurements.

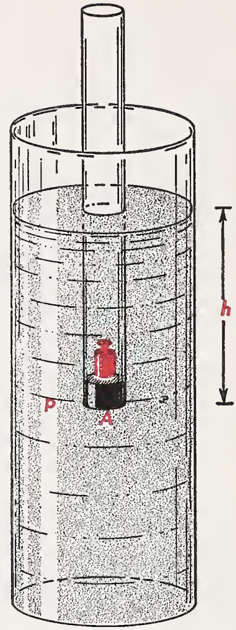


Fig. B. Floating cylinder for measuring liquid pressure.

Object. To determine the pressure at different depths within a liquid and to establish the relation between pressure and depth.

Procedure and Measurements. With the weighted tube in the water, slide a rubber band over the tube and down to the water level. Remove the tube and measure the depth h. Weigh the tube and record its mass M along with h in a table of four columns. Measure the outside diameter of the tube and record as d below the table.

Add a 50-gm weight to the lead shot at the bottom of the tube, insert the tube upright in the water, mark the water level with a rubber band, and record the depth h as trial 2. Repeat this procedure for a total of five trials, adding 50 more grams with each trial and recording the depth h in Table 2.

Dissolve a quantity of salt in the water

and repeat the above experiment. Use the same weights in the tube as before and record the depth for the five trials.

Data. We will assume that the experiment has been carried out and the data recorded as shown in Table 2.

Table 2. Recorded Data

Trial	Mass M (gm)	Water h (cm)	Salt Water h (cm)
1	375	30.0	26.6
2	425	33.6	30.0
3	475	37.8	33.9
4	525	41.7	37.0
5	575	45.8	40.8

$d = 4.0$ cm

Calculations and Results. To complete this experiment you should make a table of four columns with headings as shown in Table 3. The results for the first trial have been computed and will serve as a guide for the remaining trials.

Table 3. Calculated Results for Water

Trial	F (dynes)	p (dynes/cm^2)	$h\rho g$ (dynes/cm^2)
1	368,000	29,300	29,400

To find the values of F for column 2, follow Eq. (6) and multiply the M values in Table 2 by 980 cm/sec^2. With the measured cylinder diameter d calculate the cylinder area A. Having found the values of F in column 2, use Eq. (1) to calculate the values of p in column 3.

Values of $h\rho g$ in column 4 are obtained from the values of h in Table 2, the density of water which is 1 gm/cm^3, and the value of $g = 980$ cm/sec^2. See Eq. (10).

Conclusions. Find the salt water density by using Eq. (3), the last value of M in Table 2, and the corresponding value of h. Use Eq. (7) to find V.

Plot a graph of h against p for the water. The vertical scale for h should go from 0 to 50 cm, and the horizontal scale for p from 0 to 5×10^4 dynes/cm^2. Draw a straight line from the origin through the plotted points.

***Properties of Matter* | Lesson 7**

DENSITY AND WEIGHT-DENSITY

In this experiment we are going to make use of the principles of buoyancy to determine the densities and weight-densities of several common materials. The method is undoubtedly similar to that used by Archimedes over 2000 years ago when he determined the density of the metal in King Hiero's crown and found it was not made of solid gold.

Theory. We have seen in previous lessons that the density ρ, and the weight-density ρ_w, of any substance are given by the relations

$$\rho = \frac{M}{V} \tag{1}$$

and

$$\rho_w = \frac{W}{V} \tag{2}$$

The density is usually given in gm/cm^3, and the weight-density in lb/ft^3.

The term ***specific gravity*** is often used to designate the relative density of a material, and it is defined as ***the weight of any given body divided by the weight of an equal volume of water.***

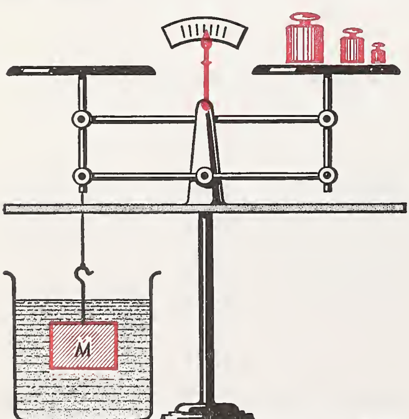
$$\text{sp gr} = \frac{\text{wt of body}}{\text{wt of equal vol water}} \tag{3}$$

Because of the fact that the gram is defined as the mass of one cubic centimeter of water, the specific gravity of any substance is given by the same number as the density in grams per cubic centimeter. For example, the density of mercury is 13.6 gm/cm^3, while the specific gravity of mercury is 13.6. The latter has no units: it is just the ratio of two weights as given by Eq. (3).

Apparatus. To experimentally determine the density of materials, we are going to weigh several objects, determine their respective volumes by the principles of buoyancy, substitute in Eq. (1), and calculate ρ.

Part 1. If the object sinks in water, we will employ the method shown in Fig. A.

Fig. A. Platform balance arrangement for weighing submerged objects.



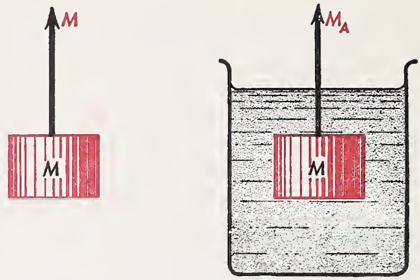


Fig. B. Weighings for materials denser than water.

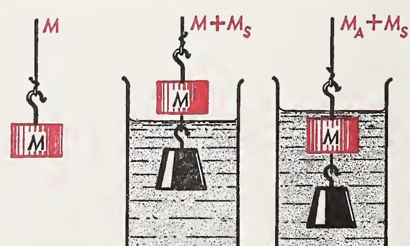
By means of a platform balance the object in question is suspended from one side and its mass M determined by adding weights to the other side. The body is then submerged in water and again weighted to find its apparent mass M_A. See Fig. B.

The loss in mass $M - M_A$ is equal to the mass of the displaced water, and therefore equal to the volume of the body. By direct substitution in Eq. (1)

$$\boxed{\rho = \frac{M}{M - M_A}} \tag{4}$$

Part 2. If the object floats in water, we will employ the same balance but use a lead weight to sink the object while weighing. As shown in Fig. C, the body is first weighed in air to find M, then with a sinker attached and submerged in water it is weighed again. Finally, with the sinker and object submerged it is weighed again. M is

Fig. C. Shows the three steps of weighing as used in Part 2.



the mass of the object in air, M_A its apparent mass in water, and M_S the apparent mass of the sinker in water.

The loss of weight between the second and third weighings is just due to the buoyancy of the displaced water. Hence the volume of the mass M is given by $(M + M_S) - (M_A + M_S)$. By direct substitution in Eq. 1 we obtain

$$\rho = \frac{M}{(M + M_S) - (M_A + M_S)} \tag{5}$$

***Object.* To employ Archimedes' principle of buoyancy to determine the density and weight-density of several metals and woods.**

Procedure and Measurements. Suspend an aluminum block, about 1 in. cube, from the scales and determine its mass in grams. Bring up a beaker of water and submerge the block, being sure the block hangs free of the glass walls. Make a table of five columns as shown in Table 1 and record the two weighings under M and M_A, respectively.

Repeat these two weighings for a similar block of brass and again for a block of iron. Record the measurements in Table 1.

Suspend a small block of maple wood, about 2 in. by 2 in. by 3 in., from the balance and determine its mass in grams. Hang a small lead weight beneath the block, bring up a beaker of water to submerge the lead only, and determine the mass $(M + M_S)$. Finally, submerge the block as well as the weight (see Fig. C) and again find the mass $(M_A + M_S)$. Record these three weighings in columns 2, 4, and 5, respectively.

Repeat these three weighings for two other blocks of hardwood and record the measured results in Table 1.

Data. Let us assume that the measurements have been made and the data have been recorded as shown in Table 1. We will now proceed with the calculations and results.

Table 1. Recorded Data

Material	M (gm)	M_A (gm)	$M + M_S$ (gm)	$M_A + M_S$ (gm)
aluminum	95.2	59.9	—	—
brass	284.0	250.3	—	—
iron	268.7	234.7	—	—
maple	172.5	—	328.7	74.7
walnut	186.4	—	342.6	64.6
oak	165.5	—	321.7	26.7

Calculations and Results. Make a table of six columns for your final calculations and use the headings shown in Table 2. The results for aluminum are already computed and will serve as a guide for computing the other five.

The values in column 2 divided by the values in column 3 give the densities of the metals, while the values in column 2 divided by the values in column 4 give the densities of the woods. Multiplying the densities in column 5 by the weight-density of water, 62.4, will give the weight-densities in column 6.

Conclusions. Conclude your laboratory report by a brief statement of what you have learned from this experiment.

Table 2. Calculated Results

Material	M (gm)	$M - M_A$ (gm)	$(M + M_S) - (M_A + M_S)$	ρ (gm/cm^3)	ρ_w (lb/ft^3)
aluminum	95.2	35.3	—	2.70	168

Properties of Matter | **Lesson 10**

DENSITY OF AIR

In our previous lesson on the atmosphere we saw how, living on the surface of the earth, we are at the bottom of an ocean of air and therefore subject to large and constant pressures. At sea level this pressure amounts to about 15 lb/in.^{2}, or, as measured with a barometer, 76 cm of mercury.

Theory. If the mercury column stands at exactly 76 cm we say we have ***standard atmospheric pressure,*** or a pressure of ***one atmosphere.*** The pressure at any depth below the surface of a liquid is given by

$$p = h\rho g \tag{1}$$

where h is the height of the liquid column, ρ is the liquid density, and g the acceleration due to gravity. Since mercury has a density of 13.6 gm/cm^3, standard atmospheric pressure is given by Eq. (1) as

$$1 \text{ atm} = 76 \text{ cm} \times 13.6 \frac{\text{gm}}{\text{cm}^3} \times 980 \frac{\text{cm}}{\text{sec}^2}$$

from which

$$\boxed{1 \text{ atm} = 1{,}013{,}000 \frac{\text{dynes}}{\text{cm}^2}} \tag{2}$$

Since barometric pressure is used so much by the Weather Bureau as an aid in predicting the weather, it has become common practice to define a new pressure unit called the ***bar.***

$$1 \text{ bar} = 1{,}000{,}000 \frac{\text{dynes}}{\text{cm}^2} \tag{3}$$

With this as a definition, we have

$$1 \text{ atm} = 1.013 \text{ bars} \tag{4}$$

A smaller unit of pressure, the ***millibar,*** is one thousand times smaller, so that

$$\boxed{1 \text{ atm} = 1013 \text{ millibars}} \tag{5}$$

It is in millibars that the atmospheric pressure is indicated on all U.S. weather maps published daily in Washington, D.C.

In addition to the slight daily variations in barometric pressure at sea level, the barometric pressure decreases rapidly with altitude. At a height of 3.5 mi the barometer stands at 38 cm, or half an atmosphere. This means that if we are 3.5 mi above the surface of the earth, half the atmosphere lies below us. At a level 19 mi above sea level 99% of the air lies beneath us.

That air has weight will be shown in this experiment. Suppose we have a hollow glass vessel, as shown in Fig. A, and we remove all the air from inside of it by means of a vacuum pump. If we now open the flask to let air rush in, the amount of air entering will depend on where we are located. Whatever amount of air would enter at sea level, only 50% as much would enter if we were 3.5 mi high, and only 1% as much would enter at 19 mi. In other words, the mass of the gas entering the evacuated flask would depend upon the pressure.

It is for this reason that the density of

Fig. A. Vacuum pump and glass flask used in finding the density of air.

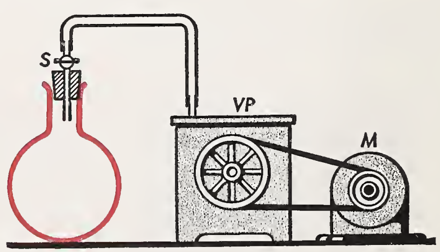


Fig. B. Evacuated flask submerged in water fills up as shown.

air, as well as the density of any gas, is generally specified as measured at standard atmospheric pressure, or one atmosphere. The densities of gases, like densities of solids and liquids, are given by the equation

$$\boxed{\rho = \frac{M}{V}} \tag{6}$$

Apparatus. The apparatus used in this experiment consists of a 3-liter (3000 cm^3), round-bottomed flask and a vacuum pump ***VP*** as shown in Fig. A. A small rectangular glass-walled aquarium tank is conveniently used as a reservoir for submerging the flask as shown in Fig. B.

Object. ***To measure the density of air at room temperature and pressure.***

Procedure and Measurements. Because of the hazards connected with the breaking of an evacuated glass vessel this experiment had best be done by the instructor while you observe and record the data.

With a stopcock and rubber stopper fitted to the flask, place the assembly on the platform of a balance and determine its mass in grams. Record as in Table 1.

Fit the vacuum pump hose over the stopcock opening and remove the air from the vessel as shown in Fig. A. Close the stopcock **S**, shut off the vacuum pump, and disconnect the vacuum pump hose. Weigh the evacuated flask assembly and again record its mass in grams.

Finally submerge the flask in the water tank as shown in Fig. B and very slowly open the stopcock. Be sure to keep the flask opening below the water surface to avoid the entrance of any air. When no more water appears to be entering the flask bring the water level inside the flask even with the water level outside. In this position only, close the stopcock.

Remove the flask from the tank, wipe the sides dry, and weigh the entire assembly. Record the mass in Table 1.

Since no vacuum pump can remove quite all of the air from a vessel, the flask will never fill completely with water. By bringing the two water levels together when closing the stopcock the residual air in the flask will be at the same pressure as the air outside, and this is the same as the pressure of the air filling the vessel in **A.**

Data. Let us assume that the experiment has been performed and we have recorded the data as shown in Table 1.

Table 1. Recorded Data

A, mass of flask in air	512.2 gm
B, mass of evacuated flask	508.6 gm
C, mass of flask and water	3362.2 gm

Calculations. To determine the density of air, your calculations can best be carried out in four steps. These steps are listed in their proper order in Table 2.

Table 2. Calculated Results

mass of air ($A - B$)	gm
mass of water ($C - B$)	gm
volume of air	cm^3
density of air, ρ =	gm/cm^3

The first two steps are self-explanatory. For the third step it should be noted that 1 cm^3 of water has a mass of 1 gm. Therefore the mass of water in grams is equal

numerically to the volume of the air removed in cm^3. For the fourth step use Eq. (6).

Results and Conclusions. Find the percentage error between the value of ρ obtained from this experiment and the accepted value of 0.00129 gm/cm^3. In writing your final report, answer the following questions:

1. Which of the three weighings requires the utmost accuracy?
2. Which, if any, requires little accuracy? Explain.

Properties of Matter | **Lesson 12**

FLUID FRICTION

When water flows through a pipe, fluid friction tends to hold it back. Not only does the viscosity set up retarding forces to flow but the attractive forces between the pipe walls and fluid molecules oppose the motion.

Theory. In Properties of Matter, Lesson 11, a demonstration experiment there shown in Fig. B was performed in which the concepts of ***velocity head, friction head,*** and ***pressure head*** were introduced. The water pressure p at the pipe entrance J is given by the height of the water column h.

Just inside the pipe at K the water is flowing with a velocity v, and the pressure is somewhat lower. The pressure difference between points J and K, called the velocity head h_v, is required to start the water from rest at J and give it a velocity v as it enters the pipe. This velocity head is given by Torricelli's theorem as

$$\boxed{h_v = \frac{v^2}{2g}} \tag{1}$$

Although the velocity v along the uniform pipe remains constant, fluid friction causes the pressure all along the pipe to fall uniformly as indicated by the water levels in the standpipes. The pressure differences between the horizontal pipe ends, both measured where the fluid has the velocity v, is called the friction head.

Finally, the pressure drop between D, a point just inside the pipe, and the point Z, just outside, is called the final pressure head. Hence the entrance pressure p is divided into three parts, such that

$$p = h_v + h_f + h_p \tag{2}$$

In this experiment we propose to determine the flow velocity v by measuring the quantity of water flowing through the pipe per second. At flow velocities usually encountered, some turbulence also occurs. One finds by experiment that the friction head h_f is proportional to the square of the flow velocity, v^2.

$$\boxed{h_f = Kv^2} \tag{3}$$

Let water flow through a uniform pipe with a velocity v as shown in Fig. A. In 1 sec a column of water v cm long will flow past any given point P, or out of the end. The volume of this water flowing per second

Fig. A. Diagram showing the relation between the size of a pipe and the rate of flow of a fluid.

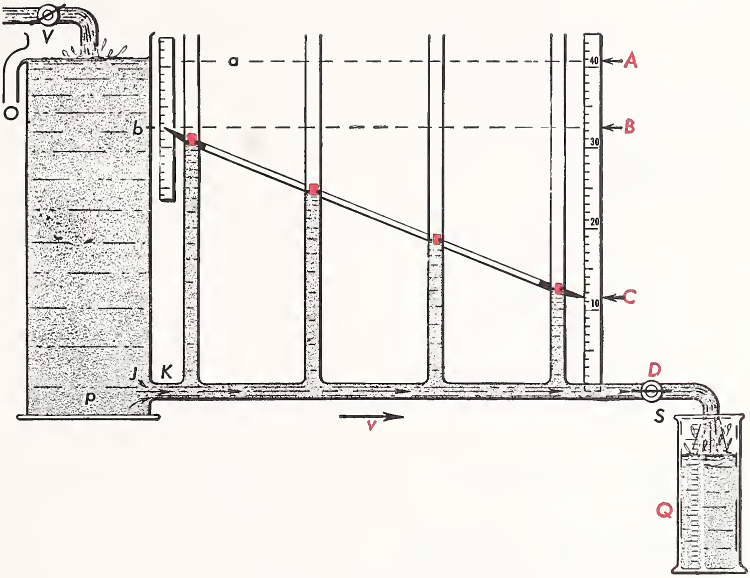


Fig. B. Apparatus for fluid-friction experiment.

is just the volume of the cylinder vA. If we now collect in a measuring cup a volume of water **Q** in a measured time interval t, we can compute the volume of water flowing per second. Therefore,

$$vA = \frac{Q}{t}$$

and, upon transposing, we find

$$\boxed{v = \frac{Q}{At}} \tag{4}$$

Apparatus. The flow apparatus is shown in Fig. B. In addition to this we will use a graduated cylinder for measuring the volume of water collected and a stop watch or clock to measure the time of collection.

Object. To determine the velocity head, the friction head, and the pressure head of water flowing through a uniform pipe.

Measurements. Open the valves **V** and **S** and adjust the water flow in and out until a steady state of conditions approximately like those shown in Fig. B exist. The overflow pipe at **O** helps maintain a constant water level at ***a***, and hence a constant pressure ***p***.

Insert the graduated cylinder in the outlet stream and collect water for 15 sec. Measure the quantity of water and record in Table 1. With a meter stick locate the points **A**, **B**, **C**, and **D**, and record them in Table 1 as shown.

Readjust valves **V** and **S** for a more rapid flow of water, and after steady conditions have been achieved, repeat all measurements and record them as trial 2. If time permits, make third and fourth trial runs. (*Note:* A small cork in each of the standpipes will float at the water surface as shown and may help in setting the straight edge along the tops of the water columns, thus serving as an aid in locating points **B** and **C**.)

Measure the inside diameter of the flow pipe. This is best done with an internal caliper. Measure and record the pipe length l.

Data. We will assume that four trial runs have been made and that the data has been recorded as shown in Table 1.

Table 1. Recorded Data

Trial	Q (cm³)	t (sec)	A (cm)	B (cm)	C (cm)	D (cm)
1	340	15	40.9	38.1	29.7	0
2	460	15	40.9	35.7	20.4	0
3	570	15	40.8	32.8	9.0	0
4	640	15	40.8	30.6	0.5	0

pipe diameter = 0.620 cm
pipe length = 56.0 cm

Calculations and Results. The calculated results are best collected in a table of seven columns with headings as shown in Table 2. The results of the first trial are included for comparison purposes and will serve as your guide in completing the calculations for the other three trials.

Table 2. Calculated Results

Trial	v (cm/sec)	v^2 (cm/sec)²	h_v (cm) calc.	h_v (cm) meas.	h_f (cm)	h_p (cm)
1	75.1	5640	2.88	2.8	8.4	29.7

First, from the measured pipe diameter $d = 0.620$ cm, calculate the pipe's cross-sectional area A. Then substitute in Eq. (4), along with the values of Q and t, to obtain v recorded in column 2.

Column 4 is calculated by use of Eq. (1), where $g = 980$ cm/sec². Columns 5, 6, and 7 are just the differences $A - B$, $B - C$, and $C - D$, respectively.

Plot a graph of your results from columns 3 and 6. The friction head h_f plotted vertically should have divisions marked 0, 5, 10, . . . 30 cm, while the v^2 values plotted horizontally should have divisions marked 0, 0.5, 1.0, 1.5, and 2.0×10^4 cm²/sec².

Conclusions. What can you conclude from the graph drawn for this experiment? Compare with Eq. (3).

Properties of Matter | **Lesson 15**

THE PENDULUM

In this laboratory experiment we are going to study pendulums of two different kinds. One is called a ***simple pendulum***, and the other is called a ***spring pendulum***.

Theory. Diagrams of a simple pendulum and a spring pendulum are shown in Fig. A. The simple pendulum consists of a small heavy weight, called a bob B, suspended by a thin cord or wire from a pivot P. When the bob is pulled to one side and released, the pendulum will swing back and forth with periodic motion.

The spring pendulum consists of a small heavy weight W suspended by a coil spring fastened to a support S. When the weight of mass m is pulled down a short distance and released, it will move up and down with periodic motion called simple harmonic motion.

In Properties of Matter, Lesson 14, on vi-

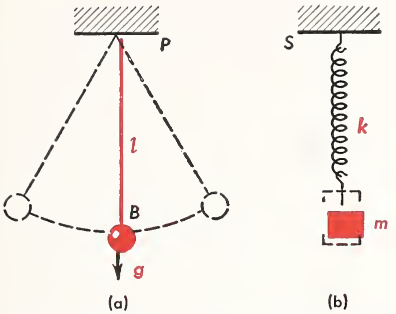


Fig. A. Diagrams of (a) a simple pendulum and (b) a spring pendulum.

brations and waves, it was stated that the periods of these two kinds of motion are given by the relations

$$T = 2\pi\sqrt{\frac{l}{g}}; \qquad T = 2\pi\sqrt{\frac{m}{k}} \qquad (1)$$

where T is the time in seconds required to make one complete vibration. In these equations, l is the length of the pendulum measured from the pivot point to the center of mass of the bob, g is the acceleration due to gravity, m is the mass of the weight W, and k is the spring constant. The constant k is determined by the stretching of the spring with different weights and the application of Hooke's law, which in Properties of Matter, Lesson 1, p. 162, we saw is given by

$$F = -kx \qquad (2)$$

In this experiment we are going to measure T and l for several different lengths of a simple pendulum and with the use of Eq. (1) compute g, the acceleration due to gravity. We are also going to measure T and m for several different weights on the end of a spring and use Eq. (1) to compute k the spring constant. Since g and k are the unknowns, we should square both equations in Eq. (1)

$$T^2 = 4\pi^2\frac{l}{g}; \qquad T^2 = 4\pi^2\frac{m}{k}$$

By transposing the measurable quantities to one side, we obtain

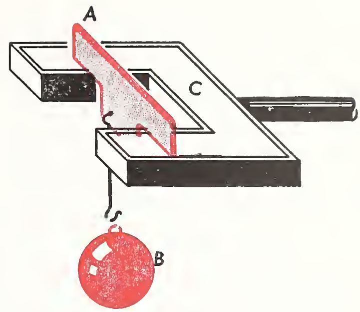


Fig. B. Pendulum support and pivot construction.

$$\boxed{g = \frac{4\pi^2 l}{T^2}} \qquad \boxed{k = \frac{4\pi^2 m}{T^2}} \qquad (3)$$

Note the similarity in the forms of these two equations.

Apparatus. The simple pendulum in this experiment consists of a solid metal sphere about 1.5 inches in diameter and several lengths of fine steel wire with small hooks at both ends of each piece. The pivot mounting is readily made from pieces of tin and arranged as shown in Fig. B. The strip of tin A, with its lower edges sharpened to a knife-edge, rests on the flat surfaces of a flat tin sheet C. The pendulum lengths are measured from the knife-edge to the center of the bob B, and need only be approximately 25, 50, 75, and 100 cm, respectively.

A small steel or bronze spring and a set of metric weights are needed for the spring pendulum. A stop watch or clock is used for determining time intervals.

Object. ***To study the principles of a simple pendulum as well as the principles of a spring pendulum.***

Procedure and Measurements. ***Part 1.*** Suspend the bob, with the shortest wire, from the knife-edge pivot. Pull the bob about 2 cm to one side and release it to swing freely. Determine the time it takes the pendulum to make 20 complete vibra-

tions. Repeat this timing process two more times and record the average value. For your data make a table of four columns as shown in Table 1.

Measure the length of the pendulum and record the result in the second column of Table 1. Repeat these measurements for each of the other three wire lengths and record ***l***, ***t***, and ***N*** as before. When the longest wire is used, measure the time for 20 vibrations with starting amplitudes of 1 cm, 4 cm, 7 cm, and 10 cm. It will be difficult to detect any real difference in the period as long as the amplitude is this small.

Part 2. Suspend the spiral spring from a rigid support and attach a metric weight to the lower end. Select a 100-gm mass for your first trial. Pull the weight down about 1 cm and release it to vibrate. Determine the time it takes to make 20 complete vibrations. Repeat this time measurement and record the average value. For these data make a table of four columns as shown in Table 2. Record the mass ***m***, the time ***t***, and the number of vibrations ***N***. Repeat these steps and measurements for masses of 200, 300, and 400 gms, and record them in Table 2.

Data. Assume that the measurements described above have been made and the data have been recorded in Tables 1 and 2. You should now proceed with the calculations.

Calculations and Results. To make your calculations for Part 1, make a table of

Table 1. Data for Pendulum

Trial	l (cm)	t (sec)	N (no. of vibrations)
1	26.4	20.6	20
2	55.8	30.2	20
3	77.3	35.4	20
4	104.2	40.8	20

Table 2. Data for Spring

Trial	m (gm)	t (sec)	N (no. of vib.)
1	100	7.7	20
2	200	10.9	20
3	300	13.4	20
4	400	15.5	20

four columns with headings as shown in Table 3. The calculations for trial 1 are

Table 3. Results for Pendulum

T (sec)	T^2 (sec^2)	$4\pi^2 l$ (cm)	g (cm/sec^2)
1.03	1.061	1040	980

already given and may be used as a guide and check upon your calculations for the others. The period ***T*** for one complete vibration is obtained by dividing the time ***t*** in Table 1 by 20. Values of ***g*** in column 4 are obtained by use of Eq. (2) and columns 2 and 3.

Make another table of four columns for Part 2 calculations, using headings as shown in Table 4.

Table 4. Results for Spring

T (sec)	T^2 (sec^2)	$4\pi^2 m$ (gm)	k (dynes/cm)
.385	.148	3950	26,700

Conclusions. The four values of ***g*** in the last column of Table 3 should be the same. Because of experimental errors they will differ slightly. Find the average value of ***g*** and then compute the percentage error between the average value and the accepted value of $g = 980$ cm/sec.

The four values of the spring constant ***k*** in column 4 of Table 4 should be the same. Calculate the average value.

HEAT

THERMAL EXPANSION

There are many instances in engineering where the expansion of solids is an important factor in design and construction. Particularly is this true in the construction of suspension bridges and railroads. It was demonstrated in Heat, Lesson 1, that not all substances expand by the same amount when heated through the same difference in temperature. This is illustrated by the linear coefficients of thermal expansion of a few common substances given in Table 1.

Table 1. Linear Coefficients of Thermal Expansion

Material	α per °C
aluminum	25×10^{-6}
brass	18×10^{-6}
copper	17×10^{-6}
gold	14×10^{-6}
iron	11×10^{-6}
platinum	9×10^{-6}
silver	18×10^{-6}
steel	8×10^{-6}

Theory. The linear coefficient of thermal expansion α may be defined as the change in length per unit length of a substance per 1° rise in temperature. Once this constant is known, the linear expansion for any sized object made of that same material can be calculated for any rise in temperature by the following formula:

elongation = α × length × rise in temperature

$$\boxed{e = \alpha l(t_2 - t_1)} \qquad (1)$$

In this equation t_1 is the original temperature of the body, t_2 the final temperature to

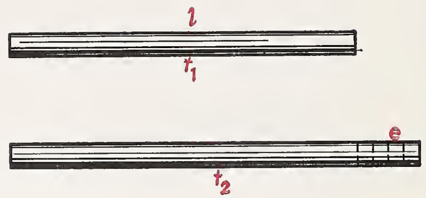


Fig. A. A metal rod expands upon heating.

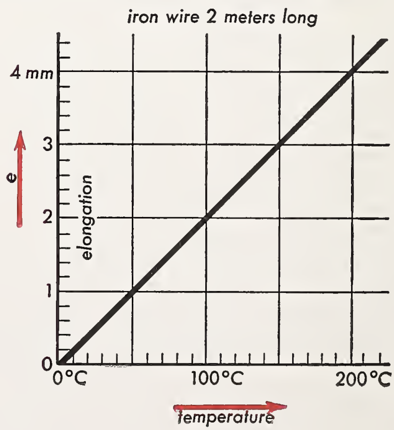
which it is raised, and l its original length.*

To see how Eq. (1) may be derived, consider a metal rod of length l and at a temperature t_1 as shown in Fig. A. If the temperature is slowly raised, and the length is carefully measured for every 10° rise, the rod is found to become longer in equal steps as shown in Fig. A.

If one plots a graph of the elongation **e** as a function of the temperature t, starting with 0°C, a graph like the one shown in Fig. B is obtained. The straight line obtained

* It is customary in formulas to use the letter t for temperature on either the Centigrade or Fahrenheit scale. When absolute temperature must be used, however, the capital letter T is used.

Fig. B. Expansion of an iron wire 2 meters long.



is characteristic of the behavior of most metals and shows that

$$e \propto (t_2 - t_1)$$

Since a rod or wire twice as long would produce double the elongation, one can also write

$$e \propto l$$

Combining these two proportionalities, one obtains

$$e \propto l(t_2 - t_1)$$

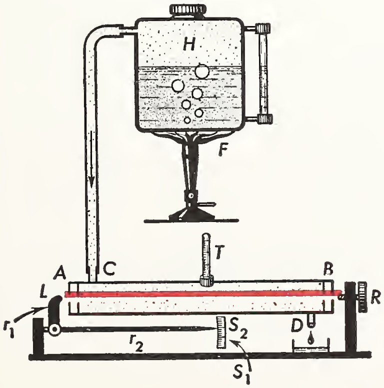
from which we obtain Eq. (1). Upon transposing Eq. (1) we obtain

$$\boxed{\alpha = \frac{e}{l(t_2 - t_1)}} \qquad (2)$$

This is the relation we will use in calculating the results of this experiment.

Apparatus. The apparatus to be used for measuring the expansion of metals is shown in Fig. C. Any one of several rods ***AB*** with cork stoppers on both ends is mounted inside a metal jacket as indicated. Steam from a small boiler ***H*** flows into the jacket at ***C***, around the rod, and out at ***D***. A thumbscrew ***R*** presses against one end of the rod, and the tip of a lever ***L*** presses against the other. The temperature can be measured at any time with the dial thermometer ***T***, and the expansion **e** is determined by the pointer readings S_1 and S_2 on the scale.

Fig. C. **Expansion apparatus showing boiler, steam jacket, thermometer, mechanical pointer, and rod.**



If r_1 and r_2 represent the lengths of the two lever arms as shown in the figure, the elongation **e** is given by

$$\boxed{e = \frac{r_1}{r_2}(S_2 - S_1)} \qquad (3)$$

Object. ***To determine the linear coefficient of thermal expansion for several common metals.***

Procedure and Measurements. Select an aluminum rod, and after measuring its length to the nearest millimeter with a meter stick, insert it in the steam jacket as shown in Fig. C. Turn up the thumbscrew ***R*** until the thrust on the lever ***L*** at the other end pushes the scale pointer to the 0.5-cm mark. Note the temperature indicated on the thermometer and record these initial measurements in a table of six columns as shown in Table 2.

Connect the steam hose from the water boiler to the jacket and watch the thermometer as the temperature rises. When the thermometer stops rising, note the temperature t_2 as well as the lever pointer reading S_2. Record these in Table 2.

Disconnect the steam hose and cool the jacket by immersing it in cold water. Select a copper rod, measure its length, and insert it in the jacket. Mount the jacket in its supports and repeat the steps described for the aluminum rod. Record all readings in Table 2.

Repeat the above measurements with two more rods, one of which is of an unknown metal.

Data. Suppose that you have completed the measurements on four metal rods and

have recorded the data as given in Table 2. It now remains to calculate the coefficient of thermal expansion.

Table 2. Recorded Data

Metal	l (cm)	t_1 (°C)	t_2 (°C)	S_1 (cm)	S_2 (cm)
aluminum	62.8	25.0	97.5	.50	1.60
copper	62.6	25.5	97.0	.50	1.22
brass	62.7	26.5	97.5	.50	1.28
unknown	62.5	26.0	97.0	.50	.96

$r_1 = 3.4$ cm; $r_2 = 32.5$ cm

Calculations and Results. Your calculations should be made and recorded in a table of eight columns as shown in Table 3. Calculations for the first trial, aluminum, are already made to serve as a guide and check upon your work for the other three.

Conclusions. Answer the following questions in your Final Report:

1. If the unknown metal is silver in color, see if you can identify the metal from its measured thermal coefficient of expansion. Look in Table 1 for values of α.
2. If an error of 1 mm were made in measuring l, what percent error would occur in the final α?
3. If an error of 1 mm were made in the value of **e**, what percent error would occur in the final α?

Table 3. Calculated Results

Metal	$\frac{r_1}{r_2}$	$S_2 - S_1$ (cm)	e (cm)	$t_2 - t_1$ (°C)	$l(t_2 - t_1)$	α Meas.	α Known
aluminum	.105	1.10	.1155	72.5	4550	.0000254	25×10^{-6}

Heat | Lesson 5

SPECIFIC HEAT

Theory. In this experiment the principles of a process called ***calorimetry*** are applied to find the ***thermal capacity***, or what is more commonly called the ***specific heat*** of a metal. The process involves the weighing of a number of objects, and the measuring of their temperatures, followed by calculations using the total heat capacity formula introduced in Heat, Lesson 3

$$\boxed{H = mc(t_2 - t_1)} \qquad (1)$$

where H is the heat in calories, m is the mass of a substance in grams, **c** the thermal capacity in cal/gm°C, and $(t_2 - t_1)$ the rise in temperature in °C.

The specific heat of a substance is numerically equal to its thermal capacity, and is defined as the ratio between (1) the number of calories H required to raise the temperature of a body and (2) the number of calories H_w required to raise an equal mass of water to the same temperature.

$$c = \frac{H}{H_w} \qquad (2)$$

Since H and H_w are in the same units,

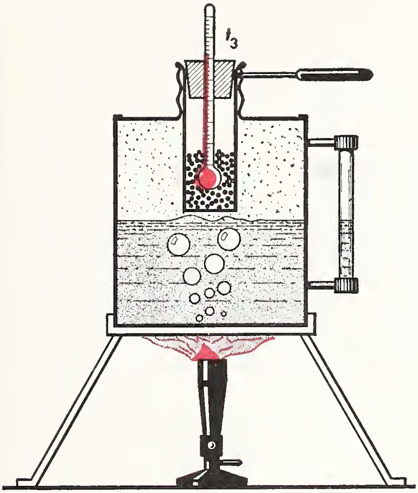


Fig. A. Steam boiler for heating metal.

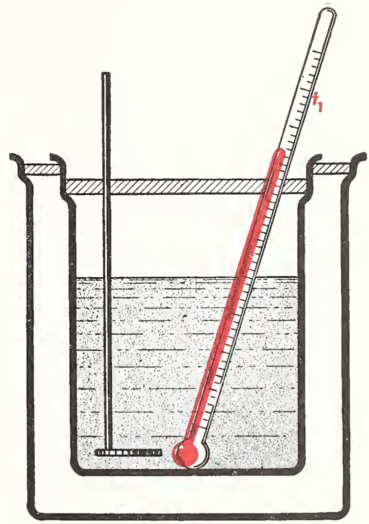


Fig. B. Diagram of a calorimeter, with a thermometer, stirrer, and water.

their units cancel out, and **c** has no dimensions. While the **c** in Eq. (1) is actually the thermal capacity, it is quite common to call it the specific heat.

Apparatus. The apparatus used in this experiment consists of two principal parts. The first part, shown in Fig. A, is a steam boiler in which a quantity of metal **m** is heated to the temperature of boiling water. The second part, shown in Fig. B, is a double-walled brass cup, called a calorimeter, containing a known amount of water, a thermometer, and a brass stirrer. Mercury or dial thermometers are used for measuring temperatures, and a platform balance is used for determining the masses of objects.

Object. To employ the principles of calorimetry to find the specific heat of a metal.

Procedure and Measurements. Put the small metal cup, the one that fits into the boiler top, on the scales and determine its mass. Pour into this cup about 500 gm of lead shot and weigh again. Record the difference in these two mass readings as **m**, the mass of the metal whose specific heat is to be determined, as in Table 1.

Insert this cup into the boiler as shown in Fig. A, and while the metal is being heated, remove the inner calorimeter cup and find its mass. Record the cup's mass as m_c. See Table 1. Now pour into this cup about 150 cm^3 of cold water and again find the mass. Record the difference between these two masses as the mass of the water m_w. The best results will be obtained if the temperature of this water is about 5 to 8° below room temperature. Weigh the stirrer and record its mass as m_s.

When the temperature of the lead shot has reached its highest point (about 99°C), note and record the temperature as t_3. Record the temperature t_1 of the water in the calorimeter cup, and then quickly lift the lead-shot container from the boiler and pour it into the water. Stir the shot and water, and record the highest temperature reached by the water-metal mixture as t_2. See Fig. C.

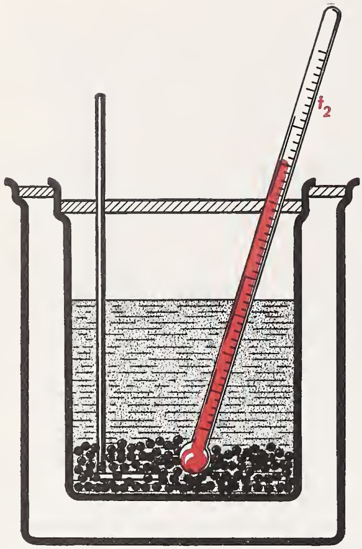


Fig. C. Calorimeter with lead shot, thermometer, stirrer, and water.

Look in Table 1 of Heat, Lesson 3, for the specific heat of the metal of which the inner calorimeter cup is composed and record it as c_c. Do the same for the stirrer and record it as c_s.

Data. Assume now that all the measurements described above have been made, and they are recorded as shown in Table 1.

Calculations. To carry out the calculations to find the specific heat of the lead metal we apply Eq. (1) to all parts of the apparatus that gained or lost heat during the mixing process. To keep things straight we put under one heading all quantities of ***Heat Lost*** and under another all quantities of

Table 1. Recorded Data

mass of metal	m	$= 512$ gm
mass of water	m_w	$= 154$ gm
mass of cup	m_c	$= 62.2$ gm
mass of stirrer	m_s	$= 31.5$ gm
initial t of water	t_1	$= 21.5°C$
final t of water	t_2	$= 28.3°C$
hot metal t	t_3	$= 99.0°C$
sp ht of cup	c_c	$= .092$
sp ht of stirrer	c_s	$= .092$

Heat Gained. In the notation of the recorded data of Table 1, these are

Heat Lost

$$H = mc(t_3 - t_2) \quad (3)$$

Heat Gained

$$H_w = m_w c_w (t_2 - t_1) \quad (4)$$

$$H_c = m_c c_c (t_2 - t_1) \quad (5)$$

$$H_s = m_s c_s (t_2 - t_1) \quad (6)$$

By conservation of energy we can now write

$$\text{Heat Lost} = \text{Heat Gained} \quad (7)$$

Hence we obtain

$$\boxed{H = H_w + H_c + H_s} \quad (8)$$

Substitute the measured values from Table 1 in Eqs. (3), (4), (5), and (6), and calculate the only unknown, the specific heat of lead c. Assume the specific heat of water, $c_w = 1.0$. As a guide for your calculations the following substitutions are given for H_s:

$$H_s = 31.5 \times .092 \times (28.3 - 21.5)$$

$$H_s = 31.5 \times .092 \times 6.8$$

$$H_s = 19.7 \text{ calories}$$

Conclusions. Compare your final calculated value of c with the accepted value and calculate the percentage error. The accepted value for lead is $c = .0310$.

Heat | Lesson 7

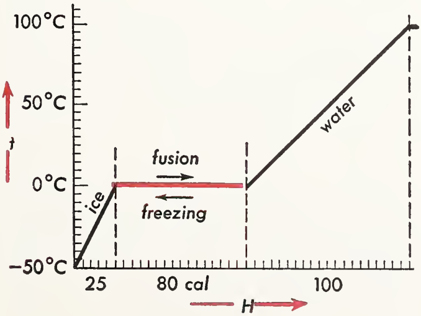
HEAT OF FUSION

When heat is continually added to a solid body, its temperature will rise until it reaches the melting point. At this temperature added heat will no longer raise the temperature but will be absorbed by the substance causing it to melt. Not until a sufficient amount of heat has been added to melt all the substance will the continued addition of heat raise the temperature of the liquid above its melting point.

Such a change of state from the solid to liquid was briefly discussed in the case of water in Heat, Lesson 3. There, in Fig. B, the melting of ice into water and the boiling of water into steam was shown graphically to illustrate changes of state. Part of this graph is reproduced in Fig. A to illustrate the latent heat of fusion of ice as 80 cal/gm. This is the constant we propose to determine in this experiment.

Theory. ***The latent heat of fusion is defined as the quantity of heat required to change 1 gm of a solid into 1 gm of liquid with no change in temperature.*** The reverse of fusion is ***solidification,*** a process in which heat is liberated by the substance as it changes from the liquid to the solid state.

Fig. A. Graph showing the change in temperature and change of state as heat is added to 1 gm of ice.



The amount of heat liberated by matter on solidification is equal to the amount of heat taken in on fusion; pure water on freezing gives up 80 cal/gm and on melting takes in 80 cal/gm.

Let L represent the latent heat of fusion and m the mass of a given substance to be fused or solidified. The quantity of heat required or liberated, as the case may be, is given by

$$\boxed{H = mL} \qquad (1)$$

If m is the mass in grams, then L is in cal/gm and H is in calories.

The latent heat of fusion for several common substances is given in Table 1.

Table 1. Heat of Fusion

Substance	L (cal/gm)
aluminum	77
copper	42
gold	16
mercury	2.8
platinum	27
silver	21
tin	14
water	80

Apparatus. The apparatus used in this experiment on the latent heat of fusion of ice is the following. Some clear cracked ice, a calorimeter with thermometer and stirrer, a platform balance, a set of weights, and a towel are needed.

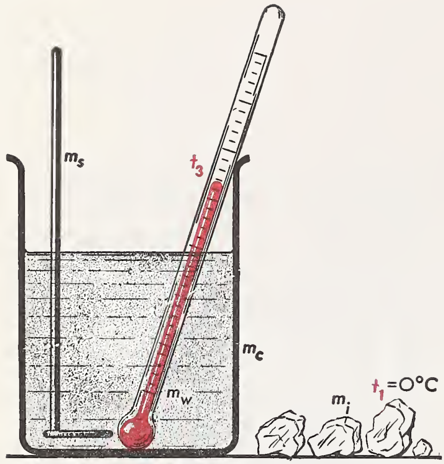


Fig. B. Calorimeter cup, stirrer, thermometer, and cracked ice for experiment.

Object. *To determine the latent heat of fusion of ice.*

Procedure and Measurements. Using the platform balance, find the mass of the stirrer. Place the inner calorimeter cup on the platform balance and find its mass in grams. Pour about 200 gm of fairly warm water, at 50 to 60°C, into the cup and again determine the mass. Record these as shown in Table 2. Replace the inner cup in its container.

Take about 40 to 50 gm of cracked ice and roll the several pieces around in the towel to remove any water from their surfaces. See Fig. B. When the ice is ready, record the temperature t_3 of water in the calorimeter cup, then quickly but carefully drop in the cracked ice, put on the cover, stir, and watch the thermometer. Look in occasionally and when all the ice has been melted, record the temperature t_2. See Fig. C. Remove the inner calorimeter cup and find its mass in grams. Record this as the mass of the cup, water, and ice.

Record the initial temperature of the ice as 0°C.

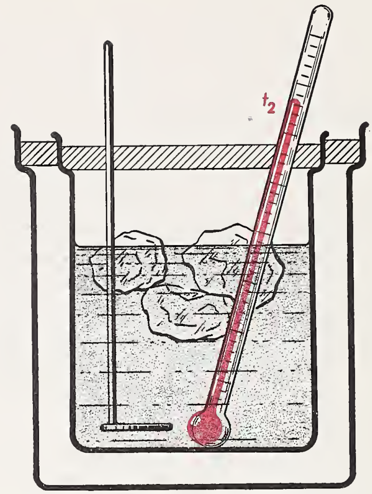


Fig. C. Assembled calorimeter with cracked ice added to water.

Data. Assume that the above measurements have been made and recorded as shown in Table 2.

Table 2. Recorded Data

mass of stirrer	m_s = 31.5 gm
mass of cup	m_c = 62.2 gm
cup + water	= 241.4 gm
cup + water + ice	= 284.7 gm
initial t of water	t_3 = 42.5°C
final t of mixture	t_2 = 19.8°C
initial t of ice	t_1 = 0°C

Calculations. To carry out the calculations to find the latent heat of fusion of ice we apply the principles of calorimetry employed in Heat, Lesson 5. For this purpose we again use the equation

$$H = mc(t_2 - t_1) \quad (2)$$

Find the heat changes H for each part of the apparatus and substance involved, and list them under one of two headings, ***Heat Lost*** and ***Heat Gained.***

The water, inner calorimeter cup, and

stirrer lose heat since the temperature of all three drop from t_3 to t_2. Their heat contributions are

Heat Lost

$$H_w = m_w c_w(t_3 - t_2) \quad (3)$$
$$H_c = m_c c_c(t_3 - t_2) \quad (4)$$
$$H_s = m_s c_s(t_3 - t_2) \quad (5)$$

Only the ice gains heat, and the amount is given by Eq. (1) and Eq. (2):

Heat Gained

$$H_i = m_i L + m_i c_w(t_2 - t_1) \quad (6)$$

By conservation of energy

$$\text{Heat Lost} = \text{Heat Gained} \quad (7)$$

and in terms of the preceding equations for H

$$\boxed{H_i = H_w + H_c + H_s} \quad (8)$$

From the recorded data in Table 1, find the mass of the water m_w as the difference between 241.4 gm and 62.2 gm. The mass of ice melted m_i is given by the difference 284.7 gm and 241.4 gm. Look up the specific heats of the metals of which the stirrer and cup are composed. If these are both brass, $c_c = .092$ and $c_s = .092$.

Substitute all known values in Eqs. (3), (4), and (5) to find H_w, H_c, and H_s. When these have been determined in calories, substitute their values in Eq. (8). On the left side of Eq. (8), substitute the measured values of m_i, c_w, t_2 and t_1. Calculate the only unknown, L, the latent heat of fusion.

Conclusions. Compare your final calculated value of L with the generally accepted value of

$$L = 80 \text{ cal/gm}$$

Compute the percentage error for this experiment.

Some ice will contain numerous bubbles partially filled with water. Why should the use of such ice be avoided in this experiment?

***Heat* | Lesson 10**

NEWTON'S LAW OF COOLING

We have seen in Heat, Lesson 6, that all objects radiate heat. The amount of heat radiated depends upon the temperature of the body and the nature of the surface area. The Stefan-Boltzmann law shows that the higher the temperature the greater is the amount of heat radiated.

$$E = kT^4$$

Black surfaces are not only the best radiators but also the best absorbers of heat. White or shiny metal surfaces are poor radiating and poor absorbing surfaces. Whatever may be the nature of its surface, if a hot body is put into a closed box or brought into a room, Prevost's law of heat exchanges applies. The hot object gives up more heat per second than it gains from the walls, and it cools. See Fig. A.

The hotter the object, with respect to the surrounding walls, the faster does it lose heat and the faster does the temperature of the body approach that of the walls.

Theory. The rate at which a hot body cools to the temperature of its surroundings is given by an empirical formula first determined by Isaac Newton. The formula

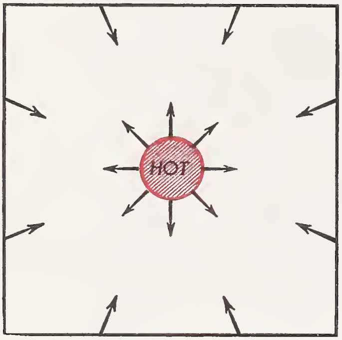


Fig. A. A hot body cools to room temperature by the process of heat exchange.

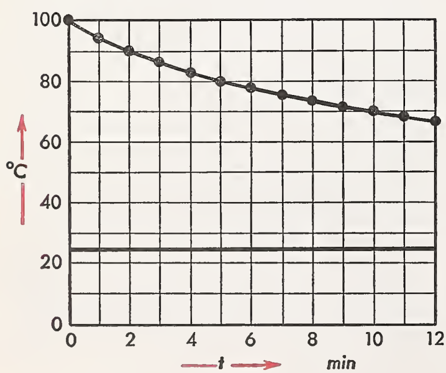
states that the rate at which heat is lost by a body to its surroundings is proportional to the difference in temperature between them. Symbolically,

$$\boxed{H = c(t_2 - t_1)} \qquad (1)$$

where H is the heat lost per second, t_2 is the temperature of the hot body, t_1 the temperature of the surroundings, and c a proportionality constant. The law holds only approximately for temperature differences that are small compared with the absolute temperature, and includes losses due to both ***convection*** and ***radiation.***

A graph showing the cooling of a beaker of hot water is shown in Fig. B. The data

Fig. B. Cooling curve for a beaker of hot water.



were taken by heating a beaker of water to the boiling point and observing its temperature with a thermometer at the end of every minute.

In repeating this experiment we will try to answer the following puzzle problem. A waiter in a restaurant serves a patron a cup of hot coffee before he is ready to drink it. Wishing to drink the coffee 8 min later, the patron wants the coffee to be as hot as possible at that time. The problem is, should he pour the cream into the coffee immediately and let it stand for 8 min, or should he pour the cream in at the end of 8 min and then drink the coffee?

Apparatus. The apparatus used in this experiment consists of pyrex beakers, two of 400-cm³ capacity and two of 50-cm³ capacity, two thermometers, a pyrex graduated cylinder, a pot of hot coffee, two Bunsen burners, and a clock or watch with a one-minute sweep hand.

Object. ***To study Newton's law of cooling as it applies to a cup of coffee under different conditions.***

Procedure and Measurements. Pour out 40 cm³ of cream into each of the two small beakers and set them one on either side of a small cardboard screen as shown in Fig. C. Measure out 300 cm³ of hot coffee in a pyrex graduate, pour it into a beaker, and place it on a ring stand to be kept at the boiling temperature by a Bunsen burner. Do the same with the second beaker.

Insert thermometers into both beakers of coffee and when they both come to the same boiling temperature, be prepared to quickly carry out the following steps.

Remove one beaker ***A*** from the burner, pour in the cream from one beaker, and set it beside the screen as shown at the left in Fig. C. Read the temperature and at the same time start the clock. At the end of about 25 sec remove the other beaker ***B*** from

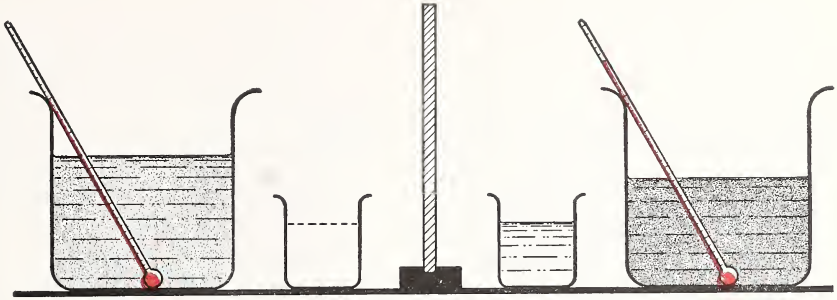


Fig. C. Two beakers of coffee, one containing cream, cool off at different rates.

the Bunsen burner, set it on the other side of the screen as shown in Fig. C, and read the temperature.

At the end of 1 min again read and record the temperature of beaker ***A***, and 30 sec later the temperature of beaker ***B***. Repeat these readings every 30 sec, alternating between the two, and record the temperatures in a table of three columns. See Table 1.

At the end of 8 min, when the temperature for beaker ***B*** has been recorded, pour the remaining beaker of cream into beaker ***B*** and quickly stir with the thermometer. Continue to record the temperatures of both ***A*** and ***B*** for four more minutes. Finally determine and record the room temperature.

Data. Assume that the measurements have been made and recorded as shown in Table 1.

Table 1. Recorded Data

Time (min)	Temperature °C	
	A	*B*
0	91.5	99.0
1	88.0	94.2
2	84.8	90.0
3	82.1	86.3
4	79.6	83.1
5	77.4	80.3
6	75.6	77.9
7	73.9	75.9
8	72.4	74.3
9	71.0	67.3
10	69.6	65.8
11	68.2	64.5
12	67.0	63.3

room temperature: 25.0°C

Calculations. There are no calculations to be made in this experiment. The results and conclusions, however, are to be drawn from the data plotted as a graph. For this purpose set up co-ordinates as shown in Fig. B. Carefully plot the points for both ***A*** and ***B*** directly above the proper time marks on the bottom scale. For example, the first readings of ***A*** and ***B***, 91.5°C and 99.0°C, respectively, should be plotted above the zero time position. The second two readings, 88.0°C and 94.2°C, should be plotted above the 1 min position, etc.

Conclusions. From the two cooling curves plotted on your graph make a brief statement of the answer to the puzzle problem stated near the beginning of this lesson. Explain briefly why the one curve crosses the other.

Heat | Lesson 12

MECHANICAL EQUIVALENT OF HEAT

Theory. Heat is but one of the many forms of energy. In Heat, Lesson 11, we saw how mechanical energy can be transformed into heat energy and how, by conservation of energy, a definite amount of heat is produced by a given amount of mechanical energy. In other words, there is an equivalence between the two forms of energy which in the mks system of units is as follows. From experimentation we will find that

$$\text{joules expended} \propto \text{calories produced}$$

or

$$\text{Work} \propto \text{Heat}$$

As an equation, we can write

$$W = JH$$

where ***J*** is the proportionality constant. By transformation, we obtain

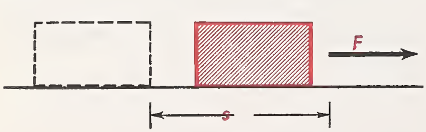
$$\boxed{J = \frac{W}{H}} \qquad (1)$$

and ***J*** is called the ***mechanical equivalent of heat.***

In order to determine the value of this fundamental constant we propose to measure an amount of ***work done W***, measure the amount of ***heat produced H***, and substitute them in Eq. (1).

The principle by which mechanical energy will be transformed into heat involves sliding friction. You will recall that the work done to slide a block along a level plane, as shown in Fig. A, is given by

Fig. A. Work done against friction is transformed into heat.



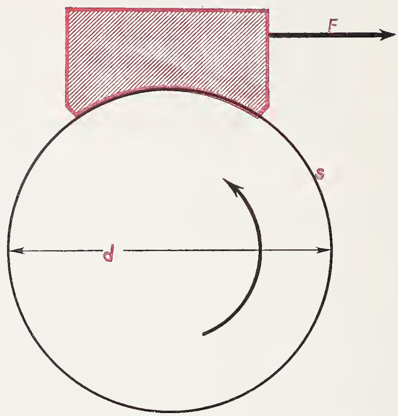


Fig. B. Friction between block and wheel produces heat.

$$W = F \times s \qquad (2)$$

Through friction this work becomes heat at the interface, and it is there that the temperature first rises.

If a block is fitted to a wheel and then slid once around the wheel, the work done is again $F \times s$, where $s = \pi d$. See Fig. B. If the block is held still and the wheel turns once around, the work done is the same. If now the wheel makes a number of revolutions, the distance through which the force acts is $\pi d \times n$, and the work done is

$$W = F \times \pi dn \qquad (3)$$

Apparatus. The apparatus to be used in this experiment consists, as shown in Fig. C, of a thin-walled, hollow cylindrical brass drum ***D*** mounted on a shaft ***S*** that is belted through the pulley ***P*** to a constant

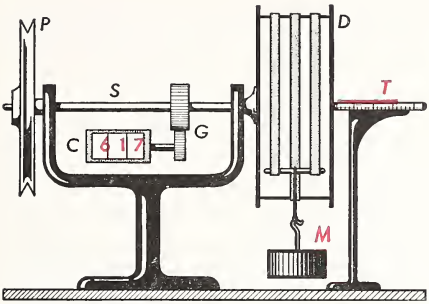


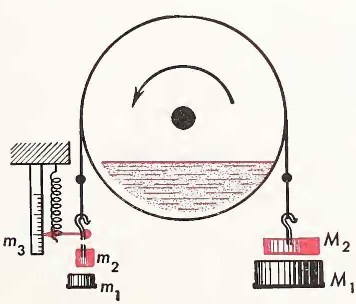
Fig. C. Principal elements in the mechanical equivalent of heat experiment.

speed motor. Around the drum are three nylon or cotton bands, wrapped around so that weights can be suspended from the ends. A known mass of water is poured into the drum, and a special bent thermometer ***T***, supported from the outside, dips into the water to give the temperature. The number of turns of the drum are counted automatically by the counter **C**. The drum is set rotating at a constant speed (about 120 rpm), and the weights are adjusted to bring the system into balance.

Two simplified diagrams of the essential elements of experiment are shown in Figs. D and E.

Object. ***To determine the joules of mechanical energy required to produce 1 calorie of heat.***

Fig. D. Diagram showing hooks and weights used to create friction.



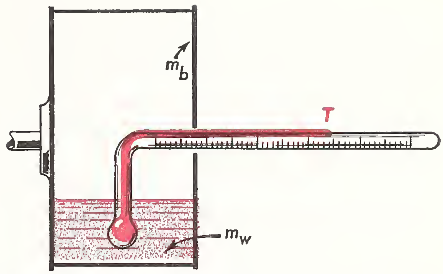


Fig. E. Thermometer position for recording temperature rise of water and drum.

Procedure and Measurements. Make a list of the quantities to be measured as shown in Table 1 and proceed as follows. Measure or weigh out about 200 gm of water at about 10°C below room temperature and pour it into the cylinder. Insert the bent thermometer, being careful to see that it is everywhere free of the rotating drum. Suspend masses from the ends of the belt and adjust until they hang free. The purpose of the spring scale $\boldsymbol{m_3}$ is to oppose the cylinder's motion and assist in retaining balance when the masses $\boldsymbol{M_1}$, $\boldsymbol{M_2}$, $\boldsymbol{m_1}$, and $\boldsymbol{m_2}$ are anywhere near balancing values.

Caution. Do not allow the bands or cylinder surface to become wet.

As the drum turns and the temperature rises, be prepared to take data in two columns as shown in Table 2. Take your first reading when the temperature is about 5° below room temperature ***t*** and the counter passes an even hundred number. Record the turns as zero and the temperature ***t***. Every one hundred turns, indicated by the counter, record the water temperature ***t***.

Continue the run until a temperature several degrees above room temperature is reached, and then stop. Measure the diameter of the drum ***d***, the masses suspended from the ribbon bands, etc., and record their values in Table 1. The drum's mass and the hook's mass are usually stamped into the metal and should be recorded.

The last two values in Table 1 are found

from the data in Table 2. Locate the value of t in Table 2 that is nearest the room temperature t. Take the temperature t_1 for the reading 200 turns above this temperature and t_2 for the reading 200 turns below this temperature. Then take the difference $(t_2 - t_1)$ and divide by 4. This then is recorded in the last row of Table 1 as the average temperature rise, $t_2 - t_1$, for 100 turns.

Data. Assume that the experiment has been performed and the data have been recorded as shown in Tables 1 and 2.

Table 1. Recorded Data

water mass	m_w = .205 kg
drum mass	m_b = .574 kg
hook mass	M_1 = .446 kg
large mass	M_2 = 1.50 kg
drum diam.	d = .155 m
room t	t = 28°C
hook mass	m_1 = .056
small mass	m_2 = .050
spring mass	m_3 = .035
sp. ht. drum	c_b = .092
number of turns	n = 100
temperature rise	$t_2 - t_1$ = ?

Table 2. Recorded Data

Number of Turns	t (°C)
0	23.2
100	24.4
200	25.5
300	26.5
400	27.4
500	28.2
600	29.0
700	29.8
800	30.5
900	31.2

Calculations. Using the data recorded in Table 1, calculate the work done W for 100 turns by using the equation

$$W = (M - m)g\pi dn \tag{4}$$

and the heat produced H by using the equation

$$H = (m_w c_w + m_b c_b)(t_2 - t_1) \tag{5}$$

It can be seen from Fig. D that M_1, M_2, and m_3 oppose the rotation of the drum, while m_1 and m_2 act to assist. Consequently we have, pulling down on the right-hand side,

$$\boxed{M = M_1 + M_2} \tag{6}$$

and pulling down on the left-hand side,

$$\boxed{m = m_1 + m_2 - m_3} \tag{7}$$

Since M and m oppose each other, the total force F, to be used in Eq. (3), is given by

$$F = (M - m)g \tag{8}$$

The total heat gained H is made up of two parts: the heat gained by the water

$$m_w c_w (t_2 - t_1) \tag{9}$$

plus that gained by the brass drum

$$m_b c_b (t_2 - t_1) \tag{10}$$

Continue the calculations by substituting measured masses in Eqs. (6) and (7), and find M and m. Insert these in Eq. (4), along with $g = 9.80$ m/sec^2, n, and d, to find W. Next, substitute directly into Eq. (5) to find H. (*Note:* To find H in calories, put masses in grams.) Finally insert W and H in Eq. (1) to find J.

Conclusions. Compare your value of J with the accepted value of

$$J = 4.18 \frac{\text{joules}}{\text{calories}}$$

and calculate the percentage error.

Heat | Lesson 15

BOYLE'S LAW

In Heat, Lesson 11, we have seen that Boyle's law is one of the three special cases of the general gas law and deals with the compression and expansion of a gas at constant temperature. The law is usually written in either one of the two following forms:

$$pV = \text{constant} \tag{1}$$

$$p_1V_1 = p_2V_2 = p_3V_3 \tag{2}$$

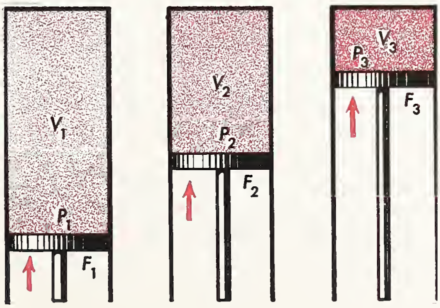
Theory. The three diagrams in Fig. A constitute a schematic representation of Boyle's law, particularly as it is written in the second form, Eq. (2).

A certain amount of gas at room temperature T is trapped above the piston in the left-hand diagram. The gas volume V_1 is maintained at a pressure of p_1 as determined by the force F_1 on the piston rod.

With increased force F_2, the piston moves up, compressing the gas and raising its temperature. In a reasonable amount of time the cylinder and its confined gas will cool down to room temperature T, and it will have a new volume V_2 and pressure p_2. If the force is increased again to a value F_3 and the gas is allowed to cool down, the new volume will be V_3 and the new pressure p_3.

Should the force on the piston be decreased, the piston will move down, the gas will cool upon the expansion, and, by waiting, the cylinder and gas will warm up to room temperature T. Hence the process of compression and liberation of heat is reversible by the expansion and absorption of heat.

Fig. A. Gas compressed at constant temperature obeys Boyle's law.



Apparatus. The laboratory apparatus to be used in this experiment is shown in Fig. B. A quantity of air is trapped by a column of mercury in a straight uniform tube **OD**. By raising the right-hand column the mercury will, in seeking to equalize the columns, compress the air into a smaller volume. By lowering the right-hand column the volume will increase and the gas pressure will decrease.

For each set position of the mercury column the volume V is read directly from the scale and pointer, and the pressure is determined by the measured difference in mercury level h. If the level B lies above A, the total gas pressure p is equal to the atmospheric pressure p_o, as read from a standard barometer, plus the height h. If B lies below A, the height h is subtracted from p_o.

Calling h plus for the arrangement in Fig. B, we have

$$p = p_o + h \tag{3}$$

or

$$p = p_o + (A - B) \tag{4}$$

and

$$V = (A - O) \tag{5}$$

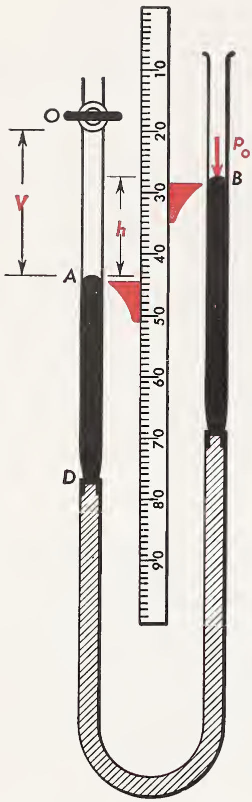


Fig. B. Apparatus assembled for Boyle's law experiment.

Care must always be taken when changing the reservoir to each new position to allow several minutes for the gas to come to room temperature. The necessity for doing this is that upon compression the gas gets warmer and on expansion it cools. Multiplying each of the measured gas pressures p by their corresponding volumes V will give a series of products, which, within the limits of experimental error, are constant.

Object. *To measure the pressure and volume changes of a gas at constant temperature and thereby verify Boyle's law.*

Procedure and Measurements. If your apparatus is such that both mercury columns are adjustable, open the stopcock at **A** and raise the left-hand column so the top of the air column is at the 20-cm mark of the meter stick. Raise or lower the right-hand column so their ends are about the same height. Pour in enough mercury to bring both columns up to about the 40-cm mark and close the stopcock. Raise the left-hand column and set **O** at the 10-cm mark.

Now lower the right-hand column as far as you can, but do not go beyond the point where the mercury level **B** is below the end of the tube and into the flexible hose. Wait 2 min for the air to reach room temperature and record the positions **O**, **A**, and **B** in a table of three columns. See Table 1. (*Note:* It is convenient to adjust the right-hand mercury column so that the mercury level **A** comes on an even centimeter mark.)

Raise the right-hand mercury column and by watching the left-hand mercury level compress the gas by 2 cm. Wait 2 min and record the levels **O**, **A**, and **B** in the table. Repeat these steps, compressing the gas 2 cm at a time until the right-hand column is as high as it will go.

Lower the left-hand column until **O** comes at the 20-cm mark. Adjust the right-hand column until the mercury level **A** has compressed the entrapped air 2 cm beyond the preceding measurements. Record these readings of **O**, **A**, and **B** as indicated in Table 1.

Continue to compress the air column 2 cm at a time by lowering the left-hand column and raising the right-hand column whenever necessary. Finally, record the atmospheric pressure from a mercury or aneroid barometer.

Data. We will now assume that the above measurements have been made and the data have been recorded as shown in Table 1.

Table 1. Recorded Data

O (cm)	A (cm)	B (cm)
10	40.0	59.9
10	38.0	54.2
10	36.0	47.4
20	44.0	50.5
20	42.0	42.0
30	50.0	42.6
30	48.0	31.3
40	56.0	27.9
50	64.0	21.0
60	72.0	9.2

Atm pressure p_o = 75.0 cm Hg

Calculations. For your calculations you should make a table of four columns with headings as shown in Table 2. The first row of values have been calculated and will serve as a guide for the other nine trials. Complete this table.

Table 2. Calculated Results

A − B (cm Hg)	p	V	pV
−19.9	55.1	30.0	1653

Results and Conclusions. Compare the products pV in the last column to see if they are constant. Calculate the average value of pV.

Plot a graph of p against V. See Fig. F in Heat, Lesson 11. For your vertical p scale label the centimeter squares 40, 50, 60, etc., up to 140 cm Hg. For the horizontal V scale label the centimeter squares 10, 12, 14, etc., up to 30. Draw a smooth curve through your plotted points. What is the mathematical term applied to this particular shape of curve?

SOUND

FREQUENCY OF A TUNING FORK

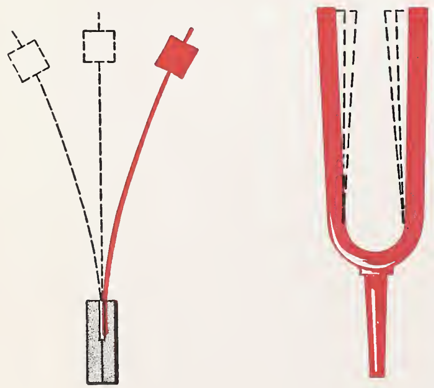
The difference between a musical sound and a noise is sometimes difficult to discern. Musical sounds involve periodic motions of some vibrating source, whereas a noise generally arises from some sudden and violent disturbance like an explosion.

In Sound, Lesson 1, we considered waves of two different kinds as well as several kinds of sources that produce sounds of different pitch and frequency. In particular the sound waves generated by the vibrating prongs of a tuning fork were introduced.

Although the transmission of sound from one point to another involves longitudinal waves, as shown in Figs. C and D, p. 258, it is customary to represent them in diagrams as transverse waves. The reason for this is simply that transverse waves are so much easier to draw.

Theory. Two vibrating objects will be used in this experiment: one is a weighted ***leaf spring,*** or ***reed,*** as shown at the left in Fig. A; and the other a ***tuning fork,*** as shown at the right. Although each part of each vibrating prong moves in a slightly curved arc, the motion along each path, if straightened out, is simple harmonic motion.

Fig. A. A weighted leaf spring, or reed, and a tuning fork.



The period T of any periodic motion (see Properties of Matter, Lesson 14, p. 199) is defined as the time in seconds required to make one complete vibration. The frequency n, on the other hand, is defined as the number of vibrations made each second of time. These two quantities, period and frequency, are so related that either one is just the reciprocal of the other.

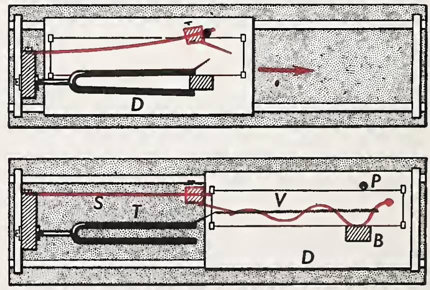
$$T = \frac{1}{n} \quad \text{or} \quad n = \frac{1}{T} \tag{1}$$

If for example the prong of a tuning fork makes 100 complete vibrations in 1 sec the frequency $n = 100$ vib/sec, and the time to make one vibration is 1/100 of a second.

$$T = \frac{1}{100}\,\text{sec} \quad \text{and} \quad n = 100\,\frac{\text{vib}}{\text{sec}} \tag{2}$$

Apparatus. To find the frequency with which the prongs of a tuning fork vibrate we make use of the apparatus shown in Fig. B. It consists of a base board about 2 ft long

Fig. B. Vibrograph apparatus showing the start and finish positions of the slider plate *D*.



and 6 in. wide with two metal bars on top to serve as guides for a sliding plate of sheet metal ***D***.

A weighted reed, or leaf spring ***S*** and a tuning fork ***T*** are clamped at one end of the board about an inch above the slider ***D***, and each carries an ink stylus at the vibrating end as shown. Each stylus is bent down so that each tip touches and draws a line on a sheet of paper ***V***. If the reed and fork are vibrating, a wavy line trace is called a ***vibrogram***, while the apparatus itself is called a ***vibrograph***.

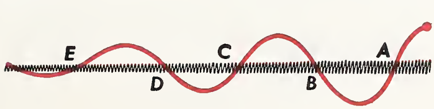
Object. ***To make a vibrograph trace and from it determine the frequency of a tuning fork.***

Procedure. Place a sheet of paper on the slider ***D*** and secure it at the corners with masking tape. Move the slider to the position shown at the top in Fig. B. Spread the tuning fork prongs so the block ***B*** slips between them and bend the leaf spring so the end is held to one side by the pin ***P***. Put a drop of ink in each stylus and slip a small piece of paper under each tip while you check to see that the ink flows freely to the paper. When this is accomplished, remove the small piece of paper.

Now move the slider steadily toward the position shown at the bottom in Fig. B, taking about 1 to 2 sec as a transit time. If all parts function properly, a vibrogram like the one shown in Fig. C will be obtained. Several trials may be necessary before a satisfactory trace is obtained.

After two or three satisfactory records have been made, use a stop watch, and determine the period and frequency of the leaf-spring pendulum. Start the pendulum vibrating and measure the time required to make 100 complete vibrations. Repeat this timing process several times and record the average time for 100 vib.

Fig. C. Vibrogram of the leaf spring and tuning fork prongs.



Measurements. Make a table of three columns on your data sheet in preparation for recording measurements from your vibrogram. Use headings as shown in Table 1. Select your best trace and label the intersections ***A***, ***B***, ***C***, and ***D*** as shown in Fig. C.

Count the number of fork vibrations between ***A*** and ***C*** and record them in column 2. Count the number between ***B*** and ***D*** and record them in column 3.

Repeat this procedure for your second and third vibrograms and record the data.

Data. Assuming the above procedure has been carried out, and the measurements have been recorded, the data should look like that recorded in Table 1.

Table 1. Recorded Data

Trials	*A* to *C*	*B* to *D*
1	65.4	66.8
2	66.0	66.5
3	65.5	67.0

average time for 100 vib of leaf spring, $t = 49.2$ sec

Calculations. From the average time for 100 vib of the leaf spring, calculate the period ***T***. This is accomplished by dividing the time ***t*** by the number of vibrations.

Find the average of the number of fork vibrations as given in Table 1 and compute the fork frequency from the relation

$$n = \frac{\text{avg number of fork vib}}{\text{period of leaf spring}} \quad (3)$$

Conclusions. Answer the following questions in your final report:

1. Does the speed of the sliding plate affect your final result?
2. Does the position of the weight on the leaf spring affect your final result?

Sound | **Lesson 5**

VIBRATING STRINGS

Vibrating strings are the basic sources of musical sounds in many of our present-day musical instruments. It is the purpose of this experiment to vary the conditions under which a string vibrates and to make a quantitative study of its behavior under greater and greater tension.

Theory. The diagram in Fig. A represents a string vibrating with standing transverse waves. The heavy line represents the position of the string at one instant and the dotted line its position one-half a vibration later.

The fundamental relation concerned with vibrating strings is to be found in the wave equation introduced in previous lessons:

$$V = n\lambda$$

or

$$\boxed{n = \frac{V}{\lambda}} \quad (1)$$

It will be noted that the total length L of any one of the loops into which the string divides is given by

$$\boxed{\lambda = 2L} \quad (2)$$

The velocity of transverse waves along a string is given by

$$\boxed{V = \sqrt{F/m}} \quad (3)$$

where, in the mks system of units, V is velocity in meters per second, F is the string tension in newtons, and m is the mass in kilograms of one meter of string.

Apparatus. The equipment used in this experiment is shown in Fig. B. It consists of a tuning fork, a string about 2 meters long, a pulley, and a set of metric weights. Although it is not necessary, an electrically driven tuning fork is the most satisfactory. Instead of having to strike the fork a blow every few seconds, an electric fork can be turned on and run continuously for as long as desired.

Fig. A. Standing longitudinal waves on a vibrating string.

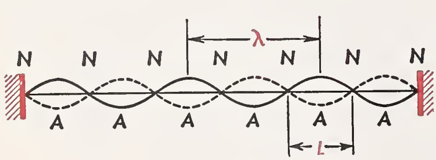
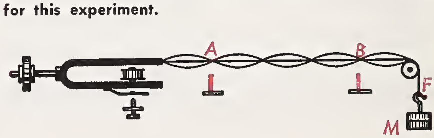


Fig. B. Tuning fork with vibrating string arrangement for this experiment.



Object. ***To determine the effect of length, mass, and tension on the vibration of a string.***

Procedure. Measure out several meters of the string to be used in the experiment and accurately determine its total mass. Record the length in ***meters*** and the mass in ***kilograms*** on your data sheet.

Fasten one end of the string to a tuning fork prong and the other end to a hooked weight over a pulley as shown in Fig. B. The horizontal string section should be about 1.5 meters long.

Set the fork vibrating and adjust the mass load M and the pulley position so the string vibrates with seven or eight loops. Note how critically the vibration amplitude depends upon string tension. Set up markers A and B at nodes to include as many loops as you can. Measure the distance between A and B, and count the number of loops included between the markers. Record these data in a table of five columns as shown in Table 1.

Gradually increase the load M until the string again responds to standing longitudinal waves. The equally spaced nodes will now be found slightly farther apart. Carefully set the markers A and B at nodes, and again measure their distance apart. Count the number of included loops and record the data as trial 2 in Table 1.

Repeat this procedure, increasing the load M each time to produce increasingly longer loops, but adjusting the total string length and mass to obtain maximum vibration amplitudes.

Data. If the above procedure has been carefully followed, the recorded data will have the general appearance of that shown in Table 1.

From the recorded length and mass of the string, calculate m, the mass per meter of string.

$$m = \frac{\text{string mass in kg}}{\text{string length in meters}} \tag{4}$$

Table 1. Recorded Data

Trial	M (kg)	A (m)	B (m)	N (loops)
1	.040	0	.795	5
2	.080	0	.896	4
3	.130	0	1.148	4
4	.190	0	1.038	3
5	.250	0	.796	2
6	.300	0	.868	2
7	.350	0	.936	2

$l = 10$ m $m = .0043$ kg

Calculations. Calculations are most easily obtained by making a table of six columns with headings as shown in Table 2. Results of the first trial have already been computed and are given as your guide for completing the calculations. Column 1 represents string tension and is given by the product Mg. For column 2 use the value of m computed from Eq. (4). Column 3 gives the average loop length L, and the values are derived from the recorded data as

Table 2. Calculated Results

F (newtons)	F/m (nt/kg)	L (m)	λ (m)	V (m/sec)	n (vib/sec)
.392	912	.159	.318	30.2	95.0

$$\boxed{L = \frac{B - A}{N}}$$

The wave lengths λ are given by Eq. (2), and the velocity V by Eq. (3) and column 2 in Table 2. The frequency n is computed by use of Eq. (1).

Results. When the calculations have been completed for Table 2, compute the average value of the frequency n as given in the last column. This should agree with the

frequency number usually found stamped in the metal of the tuning fork.

Plot a graph of the results. A chart ten squares wide by ten squares high will be adequate. Centimeter graph paper is quite satisfactory for this. Plot the wave velocity ***V*** vertically, labeling the division marks 0, 10, 20, 30 . . . 100 m/sec. Plot the wave length λ horizontally, labeling the divisions 0, 0.1, 0.2, 0.3 . . . 1.0 m. The graph line should pass through the origin.

Conclusions. What can you conclude from the graph drawn in this experiment?

Sound **| Lesson 7**

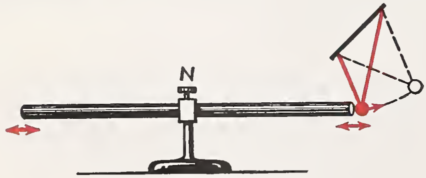
RESONATING AIR COLUMN

In this experiment we are going to produce standing longitudinal waves in a metal rod and use the resulting rod vibrations to generate standing longitudinal waves in a column of air.

An interesting demonstration of longitudinal waves in a solid is shown in Fig. A. A metal rod about 4 mm in diameter and 1 m long is clamped tightly at the center in a rigid support. With a little alcohol or rosin on a cloth, the rod is stroked from the center toward the free end. After a few strokes the rod will sing out with a high-pitched note indicating it is vibrating. That the vibrations are longitudinal is shown by the bouncing of a small ball suspended by two cords at the far end.

Vibration modes giving rise to the first three harmonics of such a rod are shown in Fig. B. The top mode gives the lowest frequency note the rod can produce and corresponds to the ***first harmonic,*** or ***fundamental.*** The others correspond to the ***second*** and ***third harmonics,*** respectively.

Fig. A. A long rod can be set to vibrate with standing longitudinal waves.



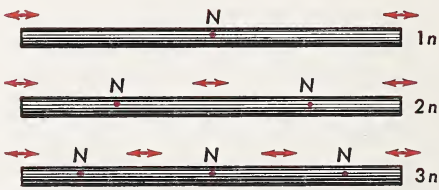


Fig. B. Longitudinal standing wave modes of vibration for a uniform rod.

Apparatus. The apparatus used in this experiment employs a rod and glass tube mounted coaxially as shown in Fig. C. When the rod is set vibrating, the disk ***A*** at the far end vibrates back and forth, sending longitudinal waves through the air column. These waves are reflected back from an adjustable plunger ***B*** at the other end. By adjusting this plunger, a position can be found where the air column will resonate with standing longitudinal waves.

A graphical pattern of these standing waves is produced inside the tube by cork dust, or lycopodium powder, distributed along the bottom as shown.

Theory. There are two vibrating systems involved in this experiment, and the wave

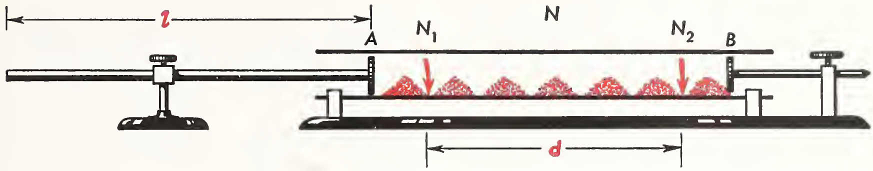


Fig. C. Diagram of apparatus used in this experiment.

equation $V = n\lambda$ can be applied to both. These, when written,

for the metal rod		for the air column
$V_m = n_m\lambda_m$		$V_a = n_a\lambda_a$
V_m	velocity	V_a
n_m	frequency	n_a
λ_m	wave length	λ_a

The subscripts simply indicate the medium to which that quantity applies. V_m, the velocity of sound in metals, is much greater than V_a, the velocity of sound in air. The two factors that are the same in this experiment, however, are the two frequencies:

$$n_m = n_a \tag{1}$$

The plunger on the rod, with its frequency n_m, sends waves of the same frequency n_a through the air column. If we solve each of the two wave equations for the frequency,

$$n_m = \frac{V_m}{\lambda_m} \qquad n_a = \frac{V_a}{\lambda_a} \tag{2}$$

we can, by Eq. (1), write

$$\frac{V_m}{\lambda_m} = \frac{V_a}{\lambda_a} \tag{3}$$

In this experiment the velocity of sound in metal becomes the unknown quantity. Solving Eq. (3) for V_m, we obtain

$$\boxed{V_m = \frac{\lambda_m}{\lambda_a} V_a} \tag{4}$$

In this experiment λ_m and λ_a will be measured, while V_a will be calculated from the formula given in Sound, Lesson 1:

$$\boxed{V_a = 331 \frac{\text{m}}{\text{sec}} + .61t} \tag{5}$$

where t is the temperature in °C.

Object. ***To study longitudinal standing waves in a column of air and determine the velocity of sound in a metal.***

Procedure. Clamp a brass rod, about 1 meter long, at its middle point in the support provided. The disk on the end should be centered within the end of the glass tube so that it does not vibrate against the sides of the glass tube.

Set the rod in vibration by stroking it slowly. A small rotation of the glass tube just prior to stroking the rod often results in a better cork dust pattern upon resonance. Adjust the plunger B by trial until a nicely scalloped pattern appears. Examine the dust near A and B, and note whether a node or antinode forms at the ends.

Measure the distance d between two nodes N_1 and N_2, and count the number of included loops N. Measure the length of the brass rod l and record the readings in a table of five columns. See Table 1.

Repeat this experiment by moving the plunger B to a new position and record the data. Make a third trial.

Replace the brass rod with an iron rod and repeat all the steps outlined for the brass. Record the data in Table 1.

Record the room temperature.

Data. Assume the above procedure has been carried out and the data have been recorded as shown in Table 1.

Table 1. Recorded Data

Trial	Metal	l (m)	d (m)	N (loops)
1	brass	.860	.510	6
2	brass	.860	.429	5
3	brass	.860	.692	8
4	iron	.796	.452	8
5	iron	.796	.334	6
6	iron	.796	.448	8

room temperature = 30°C

Calculations. Use Eq. (5) to calculate the velocity of sound in air for the recorded room temperature.

Make a table of five columns and label them as shown in Table 2. Calculations for trial 1 have already been made and will serve as a guide in computing the others.

Table 2. Calculated Results

Metal	λ_m (m)	λ_a (m)	$\frac{\lambda_m}{\lambda_a}$	V_m (m/sec)
brass	1.72	.170	10.1	3520

Since the vibration mode of the rod in this experiment is that of the fundamental, or first harmonic, as shown at the top in Fig. B, the length of the metal rod l is just half a wave length.

$$\boxed{\lambda_m = 2l} \tag{6}$$

From this relation and the recorded values of l, the calculated λ_a are obtained from columns 4 and 5 of Table 1. (Note that each cork dust loop is half a wave length.) The final velocities V_m are computed from column 4 of Table 2, the velocity V_a from Eq. (5) and substitution in Eq. (4).

Results. Assume that the correct values of the velocity of sound in metals are

for brass, $V_m = 3500$ m/sec
for iron, $V_m = 5000$ m/sec

Find the average value of the velocities measured for each metal and calculate the percentage error.

Sound | **Lesson 10**

SPEED OF SOUND

There are many different ways of measuring the speed of sound. It is the plan of this experiment to fill a glass tube with a known kind of gas, set the column vibrating with standing longitudinal waves, and, from the known frequency of the wave source, calculate the speed of sound in that gas. This is to be done with several gases.

Theory. Suppose that a glass tube containing a gas, like air, is arranged as shown in Fig. A, with a tuning fork at the open end of the tube and a plunger that can be moved up or down from the other end. Sound waves from the tuning fork travel down the tube and reflect back from the face of the plunger.

If the plunger is moved up or down, certain positions can be located where the two oppositely directed wave trains set up standing waves and the gas column sings out in resonance. Under these conditions a node N is always to be found at the face of the plunger and an antinode near the open end.

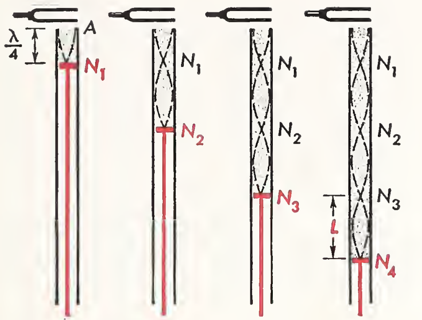


Fig. A. Different lengths of gas column will resonate to the same tuning fork.

Actually, the antinode at ***A*** is about four-tenths the diameter of the tube beyond the tube end.

The basic principles here involve the wave equation

$$\boxed{V = n\lambda} \qquad (1)$$

The wave length λ is just twice the length ***L*** of one loop.

$$\boxed{\lambda = 2L} \qquad (2)$$

It will be noted that the first resonant node N_1 occurs when the resonating gas column has a length of $L/2$, or $\lambda/4$.

Apparatus. The apparatus used in this experiment is shown in Fig. B. It consists of a glass tube about 75 cm long, connected at the bottom by a flexible hose ***H*** to a water reservoir ***R***, and a set of three tuning forks of different frequency. By raising or lowering the water reservoir, the water level in the glass tube is raised or lowered. In this way the plunger surface of Fig. A becomes the water surface in Fig. B, and the air column above the water can be adjusted in length to resonate to any one of the three tuning forks.

In performing the experiment only the top, or first, resonant node N_1 of each gas column will be located. While the other

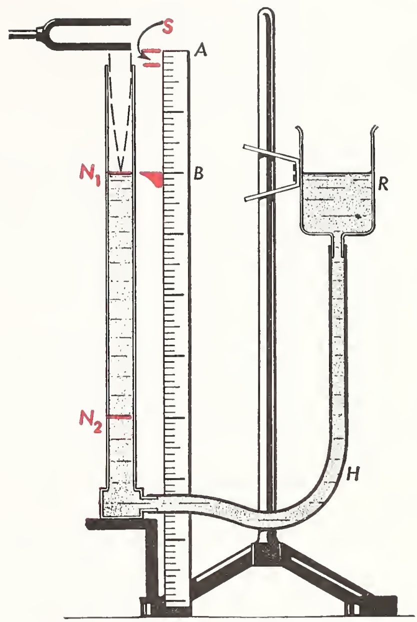


Fig. B. Apparatus for determining the speed of sound.

nodes can be found and recorded if the tube is long enough, the top one sings out most loudly.

Object. ***To measure the speed of sound in air and in other gases by means of standing waves in a resonating gas column.***

Procedure. Measure the inside diameter ***d*** of the glass tube. Multiply this diameter by 0.4 and set the zero end of the meter stick at a distance ***s*** above the end of the tube, as shown in Fig. B.

$$s = 0.4 \times d$$

This automatically sets the end of the meter stick at the topmost antinode ***A***. Read and record the room temperature.

Now select the tuning fork of highest frequency, hold it over the top end of the glass tube, and strike it a blow with a rubber

mallet. With the water level close to the top of the tube, slowly lower the reservoir and listen closely for the first resonance. Raise and lower the water level around this area until you feel the position marker is well located at N_1.

Make a table of four columns as shown in Table 1 and record the resonant position of the water level B in meters. Tuning forks are universally marked with their vibration frequency, and this should be recorded in Table 1 under n.

Select the second tuning fork and repeat the above steps of carefully locating the water level at which the tube sings out in resonance. Record the position B and frequency n.

Repeat these steps with the third fork as trial 3.

If ***carbon dioxide gas*** is available, either from a chemical generator or from a pressure tank, lower the water level in the glass tube until it is close to the bottom and insert a rubber hose down into the air column from the top. With the end of the hose under water, bubble in carbon dioxide gas until you think it has driven all the air from the tube.

Remove the rubber hose and, with the medium-frequency tuning fork held at the top of the gas column, slowly raise the water level and locate the resonance point B. Since raising the water level drives out CO_2 at the top, any lowering of the water level will draw in air and give a spurious result. Consequently, lower the water level, fill again with CO_2, and again locate the resonance position as the water level rises.

After several tries have been made, record the best position of B as well as the fork frequency n.

Ether vapor can be used as a third gas in this experiment. Lower the water level in the glass tube and then pour in about 2 cm^3 of the liquid ether. After running down the tube and spreading over the water, the ether will quickly evaporate, rise, and fill the tube. Before it has all evaporated, raise the water level and locate the point B where resonance with the medium frequency tuning fork occurs. Repeat this procedure until you are reasonably satisfied you have found the best position for B, and then record.

Data. Assume that the above steps have been carried out and that the data have been recorded as shown in Table 1.

Table 1. Recorded Data

Trial	Gas	n $\left(\frac{\text{vib}}{\text{sec}}\right)$	B $\lambda/4$ (m)
1	air	528	.163
2	air	440	.196
3	air	264	.330
4	CO_2	440	.153
5	ether	440	.114

room temperature = 28°C

Calculations. Your calculations should be carried out by first making a table of four columns as shown in Table 2. Calculations for the first trial set of data are included to serve as a guide for the others. Complete these calculations for other trials.

Table 2. Calculated Results

Gas	n $\left(\frac{\text{vib}}{\text{sec}}\right)$	λ (m)	V $\left(\frac{\text{m}}{\text{sec}}\right)$
air	528	.652	344

Results. Find the average value of your experimental determinations of the speed of sound in air. Compare this average value with the speed computed from the formula $V = 331$ m/sec $+ .61\ t$, and find your percentage error.

LIGHT

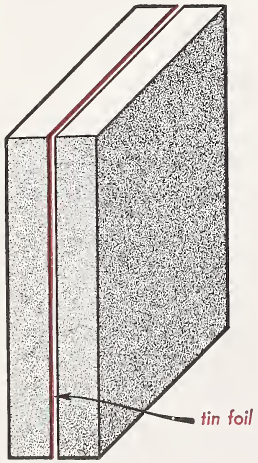
PHOTOMETRY

Photometry, we have seen, is a term applied to the experimental process by which the relative intensities of two light sources are compared and measured. One of these sources is usually of known candle power, or luminance, and the other is one of unknown candle power or luminance.

Apparatus. The fundamental principles upon which photometry is based involve the rectilinear propagation of light, the inverse square law, and the ability of the observer to adjust the distances of the two light sources so that each one produces equal illumination on a screen.

While photometer screens of many kinds and descriptions have been invented to assist the observer in making precision distance settings, a very simple yet accurate one will be used in this experiment. As shown in Fig. A, it consists of two blocks of paraffin, each about 3 in. square and $\frac{1}{2}$ in. thick, with a sheet of tin foil between them. This unit is mounted in a small cardboard or wooden box, open at both ends and one side as shown at the center in Fig. B.

Fig. A. Paraffin blocks separated by tin foil make an excellent photometer.



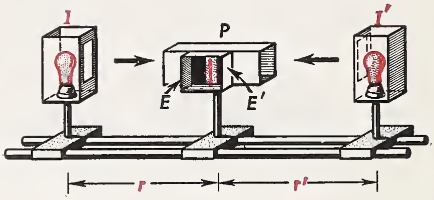


Fig. B. Photometer arrangement for measuring candle power.

The two hollow boxes on either side of the photometer ***P*** contain the two light sources, the known I' and the unknown I. All three are mounted on two parallel bars and are free to be moved. When such a photometer is moved back and forth along this optical bench, a position is easily located where the edges of both paraffin blocks appear equally bright.

Light from each lamp entering the paraffin block facing it is scattered throughout that block only. Being side by side and practically touching each other, the blocks can be easily matched, thereby indicating a position of equal illumination from the two sides.

Theory. Let I represent the unknown candle power of any lamp, and I' the known candle power of a lamp we will call the standard. As these lamps are set up in Fig. B, lamp I produces an illuminance ***E*** on one paraffin block of the photometer and I' produces an illuminance ***E'*** on the other.

By the inverse square law, Light, Lesson 2, we can write

$$E = \frac{I}{(r)^2}$$

and (1)

$$E' = \frac{I'}{(r')^2}$$

where r and r' are the distances to each of the lamps as shown. If the photometer P is set for matched paraffin blocks, the two illuminations are equal and we can write

$$E = E' \tag{2}$$

Equating the right-hand sides of Eq. (1), we obtain

$$\frac{I}{(r)^2} = \frac{I'}{(r')^2} \tag{3}$$

Solving this equation for the unknown I, we obtain

$$\boxed{I = I' \frac{(r)^2}{(r')^2}} \tag{4}$$

In this experiment we are going to take each one of several tungsten filament lamps, set them up one at a time on an optical bench with a lamp of known candle power I', set the photometer P for equal illuminance, and measure the lamp distances r and r'. When these measured values are substituted in Eq. (4), we can calculate I. The lamps to be used may be purchased at various stores, and are rated at 15, 25, 40, 50, 60, 75, and 100 watts, respectively.

Object. ***To measure the candle power of several light bulbs and to compute their efficiency.***

Procedure. Standard lamps of known candle power, burning under specified voltage and current, are available at laboratory supply houses. If a standard lamp is not available, select a new 60-watt, inside frosted, lamp bulb and assume its candle power is 66.0.

Place your standard lamp in one lamp holder socket and a 15-watt lamp in the other. Set the lamp centers exactly 80 cm apart and leave the boxes in this position throughout the experiment. Move the photometer P back and forth, and locate the equal brightness position. A little practice at this will enable you to repeat the setting each time you try. Now measure the distance r and record the interval in a table of four columns as shown in Table 1. The distance r' need not be measured, but recorded as the difference between the total distance, 80 cm minus r.

Replace the 15-watt lamp by one specified as 25 watts. Repeat the setting of the photometer P and record the measured distance r and the distance r'.

Repeat the procedure outlined above for each of the other lamps in order of increasing wattage and record the measurements in Table 1.

Data. We may assume that the above steps have been carried out and the data recorded as shown in Table 1.

Table 1. Recorded Data

Lamp Watts	I' (c.p.)	r (cm)	r' (cm)
15	66.0	23.5	56.5
25	66.0	28.8	51.2
40	66.0	34.4	45.6
50	66.0	37.5	42.5
60	66.0	40.0	40.0
75	66.0	42.7	37.3
100	66.0	46.1	33.9

Calculations. Make a table of four columns with headings as shown in Table 2. Calculations for the first lamp have already

Table 2. Calculated Results

Lamp Watts	I (c.p.)	I (lumens)	$\frac{\text{c.p.}}{\text{watt}}$
15	11.4	143	.76

been included and will serve as a guide in completing the others.

The values of I in column 2 are computed by means of Eq. (4) and the values of r, r', and I' recorded in Table 1. Since 1 c.p. = 12.57 lumens, values of I in column 3 are computed from those in column 2 by multiplying by 12.57. Values in column 2 divided by those in column 1 will give values of c.p./watt in column 4.

Results. Plot a graph of output candle power against input watts. The vertical scale for c.p. should be labeled 0, 10, 20, 30 . . . 130 c.p., while the horizontal scale should be labeled 0, 10, 20 . . . 100 watts. Centimeter graph paper is conveniently used here.

Plot the graph points with great care. Most higher wattage lamps are filled with nitrogen and argon gas at atmospheric pressure, while the smaller 15- and 25-watt lamps are highly evacuated. Excluding these two low wattage lamps, draw a straight line, as best you can, through the plotted points for the others. The intersection of this line with the watt's axis will show the approximate energy loss in these lamps due to (1) heat conduction to the lead and support wires, (2) the absorption of some light by the gas, and (3) bulb and base absorption of light.

Starting at the graph origin, draw a smooth curve through the plotted points for the 15-, 25-, and 40-watt lamps.

***Light* | Lesson 5**

REFLECTION FROM PLANE SURFACES

The image of any object seen in a plane mirror is just as far behind the mirror as the object is in front of it. It is the purpose of this laboratory lesson to try to verify this statement by experimentally tracing light rays incident on and reflected from a mirror, graphically locating an image, and then measuring the object and image distances from the reflecting surface.

Theory. The basic principles involved in this experiment are concerned with (1) ***the rectilinear propagation of light*** and (2) ***the law of reflection.*** The law of reflection, as demonstrated in various ways in Light, Lesson 4, states that the angle of incidence is always equal to the angle of reflection:

$$\boxed{\text{angle } i = \text{angle } i'} \qquad (1)$$

It is to be understood that the incident ray, the reflected ray, and the normal to the surface all lie in the same plane and that the two angles i and i' are on opposite sides of the normal.

To employ the established fact that light travels in straight lines we make use of a principle often used by surveyors. In making a plan drawing to scale, they place their paper on a ***plane table*** that has been carefully leveled and use a sighting device for establishing line directions to distant points. The principle is illustrated by three pins **A**, **B**, and **C** in Fig. A.

Fig. A. A straight line path of a light ray can be established by sighting along and lining up points.

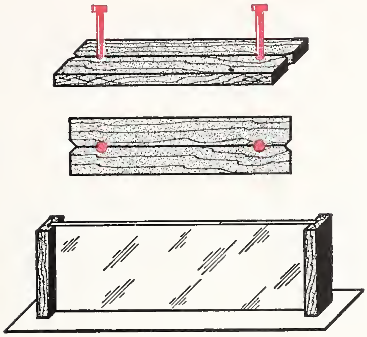


Fig. B. Sighting pin block and mirror mounting as used in this experiment.

To establish the direction of a point ***A*** from a point ***C***, the eye is located behind ***C*** and the third pin is moved into a lined-up position. Light traveling in a straight line from ***A*** to ***E*** must pass directly over ***B*** and ***C***.

Apparatus. A suitable sighting device can be made for this experiment by driving two pins, or small wire brads, into a block of wood, as shown in Fig. B. The block is conveniently made from $\frac{1}{4}$-in. plywood about 3 in. long and $\frac{3}{4}$ in. wide. After making a V-shaped notch in the ends, a straight line is drawn through their centers as shown. Two pins or brads are then located exactly on this line and accurately driven vertically part way into the wood.

A pocket mirror about 2 by 3 in., or a strip of glass cut from a larger mirror is quite adequate. Two square blocks of wood, each with a groove for the glass to fit into, may be used to set the mirror upright on a sheet of paper.

Several sheets of paper $8\frac{1}{2}$ by 11 in., a centimeter rule, a protractor, a sharp pencil, and a flat board of soft wood 9 by 12 in., or larger, are needed.

Object. ***To make a study of the law of reflection and the images seen in a plane mirror.***

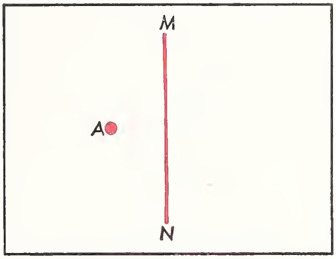


Fig. C. Showing preliminary steps in drawing.

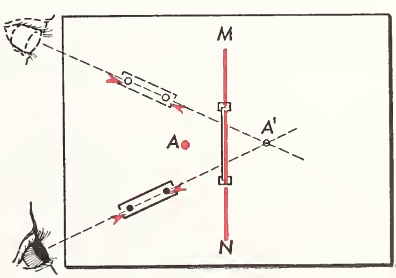
Procedure. Use masking tape to fasten a clean sheet of paper to the board. Use your ruler and draw a straight line across the center of the paper as shown in Fig. C. Label this line ***MN***. Locate a point ***A*** about 4 cm from this line and near the center as shown.

Place the mirror upright on the paper so that the back silvered surface is exactly on the line as shown in Fig. D. Stick a pin into the paper and wood at the point ***A***, being sure it is straight and vertical. This pin ***A*** becomes the object, and ***A′*** as seen in the mirror is its image.

Place the sighting-pin block on the paper and, with one eye close to the table top and looking into the mirror, line up the two sighting pins with the image ***A′***. Holding this block down with one hand, use your pencil and make two marks on the paper at the tips of the two notches.

Move the sighting pins to the other side of ***A***, shown dotted in Fig. D, and again

Fig. D. Illustration showing two sighting positions.



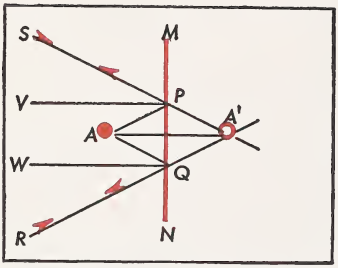


Fig. E. Completed line drawing ready for measurement.

line up with the image ***A′***. Mark the notch positions as before, and then remove all objects from the paper.

Using your ruler, draw straight lines through each pair of notch marks and mark their intersection point ***A′*** as shown in Fig. E. Draw another line through ***A*** and ***A′***, and two additional lines from ***A*** to points ***P*** and **Q**. With your protractor, erect perpendiculars from points ***P*** and **Q** as shown.

Before proceeding with measurements, make a table of four columns with headings as shown in Table 1. Measure the perpendicular distances from ***A*** to ***MN*** and ***A′*** to ***MN***, and record in columns 1 and 2. Measure the angles ***AQW*** and ***RQW*** with your protractor, and record them as angles ***i*** and ***i′***, respectively. Measure the angles ***APV*** and ***SPV***, and record them as a second pair of angles ***i*** and ***i′***.

Replace this paper with a clean sheet of paper, draw a line ***MN*** as before, and locate a point, ***A***, 7 cm in front of ***MN***. Repeat all steps outlined above and record the data as trial 2 in Table 1.

If time permits, repeat the experiment with the point ***A*** located somewhat to one side but 5 cm from the line ***MN***. Take both lines of sight from the same side of the normal of ***A*** to ***M***.

Data. Assume that the above experiment has been performed and the data recorded as shown in Table 1. Note in your experiment that the light rays travel from ***A*** to the mirror and then off to the eye and not the reverse.

Table 1. Recorded Data

A to *MN* (cm)	*B* to *MN* (cm)	Angle *i* (deg)	Angle *i′* (deg)
4.0	3.9	38.5 26.0	38.3 26.2
7.0	7.0	34.0 36.5	34.4 36.5
5.0	5.1	47.0 26.2	47.5 26.0

Results. There are no calculations required in this experiment, and your laboratory report consists principally of the sheets of paper on which you made your drawings.

Conclusions. Compare the pairs of distance values given in columns 1 and 2. Compare the pairs of angles in columns 3 and 4. What can you conclude from these comparisons? Make a brief statement of what you have learned from this experiment.

Light | Lesson 8

INDEX OF REFRACTION

When light crosses the boundary separating two transparent media, like air and water or air and glass, the light changes its direction at the boundary. As we have seen in Light, Lesson 7, this behavior is called ***refraction***, and a quantitative account of the bending is given by a general rule called ***Snell's law***.

In this experiment we will allow a ray of light to be refracted at the surface of glass, measure the incident and refracted angles of this light, and from these determinations calculate the ***refractive index*** of glass.

Theory. The basic principles involved in this experiment were presented in Light, Lesson 7, and may be expressed by the relatively simple relation known as Snell's law:

$$\boxed{\frac{\sin i}{\sin r} = \mu} \qquad (1)$$

As shown in Fig. A, ***i*** represents the angle the incident light ray makes with the surface normal ***NN'***, and ***r*** the angle the refracted ray makes with the same normal. When angles ***i*** and ***r*** are measured in degrees, we can look up the sine of these angles in any table of the natural functions. These numbers can be substituted in Eq. (1) and the refractive index μ calculated.

In effect, Snell's law says that the sine of the angle of incidence is directly proportional to the sine of the angle of refraction for all angles. If, therefore, the proportionality constant μ turns out to have the same value for all angles of incidence, the law can be considered verified.

The glass to be used in this experiment has the shape of one-half of a right circular cylinder as shown in Fig. B. When a ray of

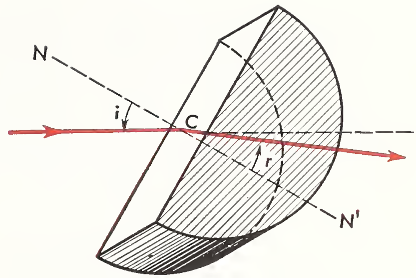


Fig. B. Refraction of light.

Fig. A. Refraction of light by glass.

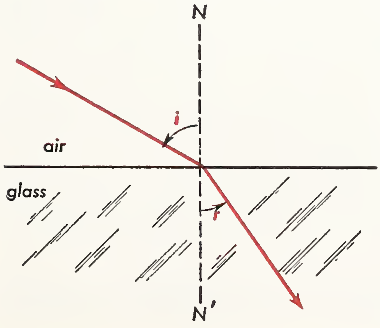
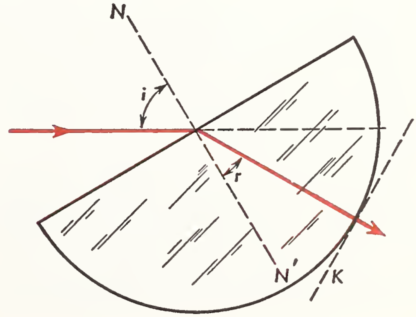


Fig. C. Refraction occurs at only one surface in this block of glass.



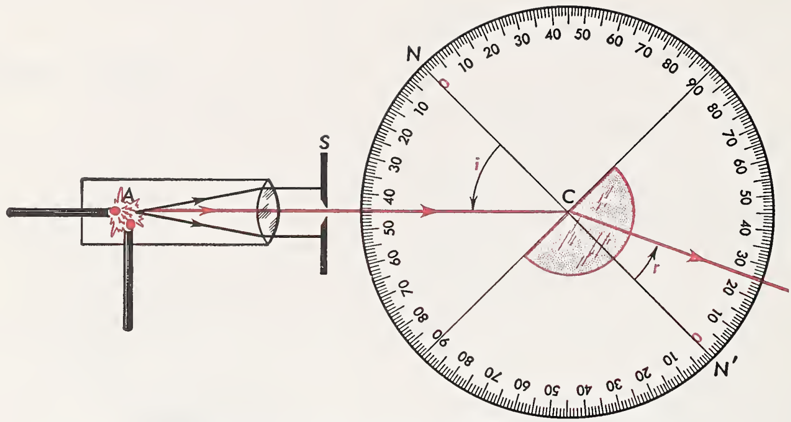


Fig. D. Hartl disk and optical parts for measuring refraction angles.

light enters the plane face at the center **C** and at an angle ***i*** with the surface normal ***NN′***, the refracted ray at an angle ***r*** will emerge from the far side of the glass without further refraction.

If the glass block is turned about **C** so as to increase the angle ***i***, the angle ***r*** will also be increased and the ray will emerge from the glass without further bending as shown in Fig. C. If the initial light ray is always incident at the center **C**, the refracted ray will always arrive at the curved surface at right angles to a tangent ***T*** drawn through that point. Since its angle of incidence at this curved surface is zero, the angle of refraction is also zero and the light travels through without bending.

Apparatus. The apparatus used in this experiment is called a Hartl disk. As shown in Fig. D, it consists of a metal disk, free to turn about its center C and around its periphery by an angular scale divided into degrees.

A glass block, as described above, is mounted at the disk center so that light from a small carbon arc, confined to a narrow ribbonlike beam by a slit **S**, crosses the disk face as shown. With the disk face painted white and the room lights subdued, the beam can easily be seen across the disk. The angles at which it enters and leaves the plane glass surface can be read directly where they cross the scale.

By leaving the light and slit fixed, and turning the disk, the angle of incidence can be changed with ease.

Object. ***To determine the refractive index of glass and thereby test Snell's law.***

Procedure. Strike the arc and adjust the slit to obtain a narrow beam across the Hartl disk. Mount the glass prism on the disk, being careful to see that its face is along the 90° line and centered exactly.

Turn the disk to 0° to see that the light enters and leaves the glass along the line ***NN′***. Record this zero reading in a table of three columns as shown in Table 1.

Turn the disk so the angle of incidence is 10° and note the angle of refraction. Record these as trial 2 in Table 1.

Repeat this procedure, increasing the angle of incidence 10° at a time, and for each case record both angles in Table 1.

Data. We will assume that the above procedure has been carried out and the

measurements have been recorded as shown in Table 1.

Table 1. Recorded Data

Trial	i (deg)	r (deg)
1	0	0
2	10	6.0
3	20	12.0
4	30	17.5
5	40	23.0
6	50	27.5
7	60	32.0
8	70	34.5
9	80	36.0
10	88	37.5

Calculations. It will be convenient to record your calculated results in a table of three columns with headings as shown in Table 2. The results of the first two trials are already completed and will serve as a guide in completing the others. A value of μ cannot be computed for trial 1 as both angles are zero.

Table 2. Calculated Results

sin i	sin r	μ
0	0	—
.174	.105	1.66

When all nine values of μ have been computed, find their average value.

Plot a graph, angle i plotted horizontally, against angle r vertically.

Conclusions. Note from your graph as well as from the table of recorded data that angles i and r are nearly proportional to each other for small angles, whereas for large angles they are not.

Snell's law requires that the sines of the angles be proportional to each other for all angles. Is this experimentally verified by this experiment? Briefly explain.

Light | Lesson 10

LENSES

In most of the hundreds of different kinds of optical instruments developed over the years, lenses in one form or another certainly play the most important role. Because they are the principal components in such common instruments as spectacles, cameras, picture projectors, binoculars, telescopes, and microscopes, it is worth while for us to make a quantitative study of lenses.

Theory. The most common form of lens is known as a positive, or converging, lens, as shown in Fig. A. Its action is such that a parallel beam of light entering one side parallel to the axis emerges from the other side converging to a focus at the focal point **F**. The distance from the center of the

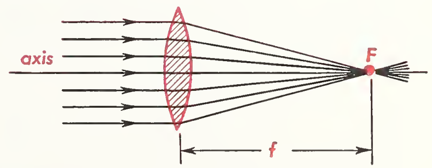


Fig. A. Parallel light comes to a focus.

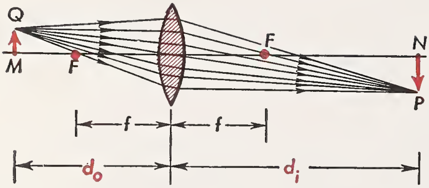


Fig. B. Image formation with a converging lens.

lens to the focal point is called the focal length f.

Such a converging lens also exhibits the useful property that if it is located at an appropriate distance from any object **O**, a real image I of that object can be formed on a screen. Rays leaving any one point of an object like **Q** in Fig. B will, after traversing the lens, come to a focus at the corresponding image point **P**. Rays leaving **M** (not shown) will come to a focus at **N**, etc.

The relation between the ***object distance*** d_o and the ***image distance*** d_i is given by the following simple equation:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \tag{1}$$

where f, as shown in Light, Lesson 9, is the focal length of the lens.

The relative sizes of object **O** and image I are given by the equation

$$\boxed{\frac{I}{O} = \frac{d_i}{d_o}} \tag{2}$$

This ratio is called the ***magnification M***, and we write

$$\boxed{M = \frac{I}{O}} \tag{3}$$

If the image is twice the size of the object, the magnification is 2, and if I is ten times the size of **O**, the magnification is 10, etc.

The plan in this experiment is to measure the size and position of an object and the size and position of the image, and from them to calculate the magnification and the focal length of the lens. To solve Eq. (1) for f we may carry out the following steps. Multiply numerator and denominator of the first term by d_i and the second term by d_o.

$$\frac{d_i}{d_id_o} + \frac{d_o}{d_id_o} = \frac{1}{f}$$

With a common denominator the two terms on the left can be collected to give

$$\frac{d_i + d_o}{d_id_o} = \frac{1}{f}$$

Inverting this equation we obtain

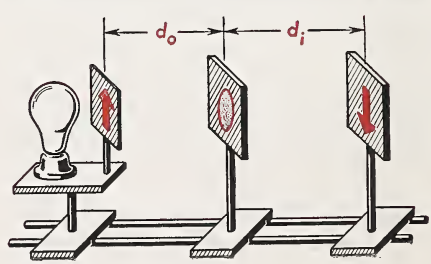
$$\boxed{f = \frac{d_i \times d_o}{d_i + d_o}} \tag{4}$$

Apparatus. The single converging lens with a focal length of 15 to 20 cm is conveniently used in this experiment. A small screen with an arrow-shaped hole cut in it, as shown in Fig. C, and a common frosted glass light bulb behind it, serves as a suitable object. Another small screen about 4 in. square makes a good image screen.

These three elements—object, lens, and screen—can be mounted on separate stands that can be moved around on a table, or they may be mounted in holders on an optical bench if available. A meter stick is used for measuring object and image distances.

Object. To determine the focal length of a convex lens and to study the laws of image formation.

Fig. C. Apparatus for studying the properties of lenses.



Procedure. Use masking tape and fasten a sheet of white paper or cardboard to the wall opposite a window of the room. Hold the lens up in front of this screen and move it back and forth until a sharp image of some distant object outside the window can be seen on the screen. Measure the distance between the center of the lens and the screen. Record this distance in centimeters as the focal length of the lens.

Set up the object, lens, and screen as close together on the table as possible and adjust their centers to the same height. Now move the object (the cutout arrow) until it is about one and a half times the focal length from the lens. Move the screen back and forth until a sharp image is formed on its surface. Measure the object distance d_o and image distance d_i, and record them in a table of five columns. See Table 1. Measure the height of the object O and the height of the image I, and record.

Increase the object distance 5 cm and then move the screen to obtain a sharp image. Again measure the object and image distances, and the object and image heights, and record.

Repeat these steps for four or five more trials, increasing the object distance 5 cm each time and recording the measurements in Table 1.

Table 1. Recorded Data

Trial	d_o (cm)	d_i (cm)	O (cm)	I (cm)
1	25.0	58.5	3.2	7.4
2	30.0	43.0	3.2	4.5
3	35.0	34.4	3.2	3.1
4	40.0	30.2	3.2	2.4
5	45.0	28.4	3.2	2.0
6	50.0	26.5	3.2	1.7
7	55.0	25.2	3.2	1.5

measured $f = 17.3$ cm

Data. Suppose the above measurements have been made and the data recorded as shown in Table 1. The directly measured focal length is given just below the table.

Calculations. Your calculations are conveniently made by recording them in a table of six columns. See Table 2. The column headings are self-explanatory as they come directly from Eqs. (4), (2), and (3). The first trial calculations are already completed and will serve as a guide for all the others.

Table 2. Calculated Results

$d_i \times d_o$	$d_i + d_o$	$\frac{d_i \times d_o}{d_i + d_o}$	$\frac{I}{O}$	$\frac{d_i}{d_o}$
1460	83.5	17.5	2.31	2.34

Results. The calculated results in column 3 are values of the focal length and should all be alike. Find their average value and compare with directly measured value under Table 1.

Plot a graph of object distance d_o against image distance d_i. The vertical scale for d_o and the horizontal scale for d_i should each be labeled 0, 5, 10, 15, . . . 70 cm. Draw a smooth curve through the plotted points. Draw a horizontal line on the graph at a height where $d_o = f$, and a vertical line where $d_i = f$. Extrapolate your curve to $d_o = 70$ cm and $d_i = 70$ cm.

Conclusions. How would your graph look (a) if d_o became very large and (b) if d_i became very large? Briefly explain.

What can you conclude about the last two columns in Table 2? How does the magnification change as the object comes closer and closer to the focal point?

MAGNIFYING POWER

A single converging lens is frequently used to magnify small objects, thereby enabling an observer to see detail not possible with the unaided eye. As illustrated in Light, Lesson 9, such usage of a lens comes under the heading of ***virtual images.***

Theory. When a lens is to be used as a magnifier, the object must be located inside the focal point as shown in Fig. A. This diagram is drawn to scale and represents an object located 3 in. from a lens of 4-in. focal length. The object-image formula may be applied to find the image distance.

$$\boxed{\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}} \qquad (1)$$

Upon substitution, we find

$$\frac{1}{3} + \frac{1}{d_i} = \frac{1}{4}$$

$$\frac{1}{d_i} = \frac{1}{4} - \frac{1}{3} \qquad \frac{1}{d_i} = \frac{3}{12} - \frac{4}{12}$$

$$\frac{1}{d_i} = -\frac{1}{12}$$

Upon inversion, we obtain

$$d_i = -12 \text{ in.}$$

The image is 12 in. from the lens, the minus sign signifying the image is to the left of the lens and virtual. The rays shown entering the eye only seem to be coming from ***I***.

As presented in Light, Lesson 10, the magnification is given by the image-to-object ratio.

This ratio ***M*** is sometimes referred to as the ***magnifying power.***

$$\boxed{M = \frac{I}{O} = \frac{d_i}{d_o}} \qquad (2)$$

In this example

$$M = \frac{12}{3} = 4$$

The image appears to the eye to be 4 times (written 4×) the size of the object.

The normal unaided human eye is able to focus upon objects as close as 25 cm or 10 in. This particular distance is called the ***near point,*** or ***distance of most distinct vision,*** and it is here that an image should be located to see the greatest detail with a magnifying lens. In the arrangement of Fig. A the light rays entering the eye are brought to focus on the eye retina. This is shown in Fig. B, where the magnified image ***I*** appears to be at the near point of 25 cm, the object **O** is just inside the focal point ***F***, and the real image is formed on the retina. Although the actual rays from the magnifier lens it-

Fig. A. A converging lens used as a magnifier.

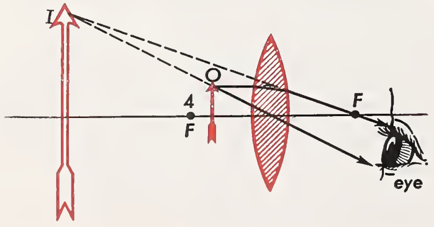
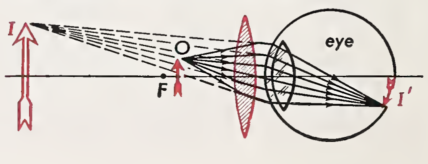


Fig. B. The virtual image *I* seen by the eye is actually a real image of *I′* formed on the retina.



self are diverging, the eye lens system converges them.

The formula for the magnification, with the image I at the near point of 25 cm, is given by

$$\boxed{M = \frac{25}{f} + 1} \quad (3)$$

where f is the focal length of the magnifier in cm. It can be seen from this formula that the shorter the focal length f, the greater will be its magnification.

Apparatus. The lenses to be used in this experiment are three in number, one having a focal length of about 10 cm, a second with a focal length of about 3 cm, and a third with a focal length of about 1 cm. Any three lenses of approximately these focal lengths are quite satisfactory.

Each lens L should be mounted in a holder and placed in line with the center of a screen S having a square opening about one-fourth of the focal length on a side. A centimeter scale R is then located on the lens axis and observed with one eye located as shown in Fig. C.

Object. ***To determine the magnifying power of a small converging lens.***

Procedure. With a small bright light as an object 20 ft or more away from the lens, find the image distance from the lens. Record this distance as the focal length of the lens. Repeat this procedure for the other lenses and record as indicated in the last column of Table 1.

Set up the longer focal length lens 25 cm from the scale R as shown in Fig. C. With one eye closed look through the lens with the other, and move the screen S back and forth until a sharp image of the square opening falls on the scale.

To be sure the image is at R, move the eye laterally with respect to the lens axis, up and down or back and forth parallel to R. If the edges of the square image stay fixed in position on the scale, proper adjustment has been achieved. If the image moves on the scale as the eye moves at the lens, the image is either in front of or behind the scale. Move the screen until no motion (no parallax) is observed.

Measure the object distance d_o, the height of the open square O, and the image height I as observed on the scale. Record these distances in a table of five columns, with headings as shown in Table 1.

Set up the second lens with its appropriate square hole screen S and locate the cm scale 25 cm away, as shown in Fig. C. Repeat the procedure outlined above and record the measurements in Table 1.

Repeat all procedures with your third lens and record the measurements.

Data. Assuming the above measurements have all been made and recorded, the data will have the appearance of those shown in Table 1.

Fig. C. Laboratory arrangement for the magnifier lens.

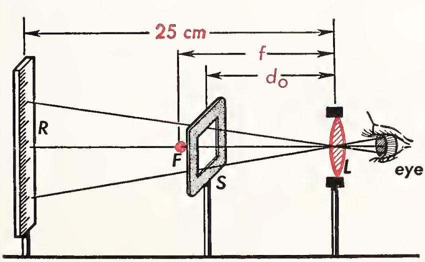


Table 1. Recorded Data

I cm rule	O square hole	d_i near point	d_o lens to square	f (cm)
8.6	2.5	25	7.3	10.4
7.1	0.80	25	2.8	3.2
6.9	0.40	25	1.4	1.5

Calculations. Your calculations are best carried out by recording them in a table of four columns, with headings as shown in Table 2. These calculations are easily carried out for all your lenses, using Eqs. (2) and (3).

Table 2. Calculated Results

$M = \frac{I}{O}$	$M = \frac{d_i}{d_o}$	$M = \frac{25}{f} + 1$	Average M

When the first three columns have been completed, each of the three values of ***M*** for each one of the three lenses should be the same. Any differences are due to experimental errors.

Calculate the average value of ***M*** and record in column 4.

Conclusions. What have you learned from this experiment?

Light | Lesson 15

PRINCIPLES OF THE MICROSCOPE

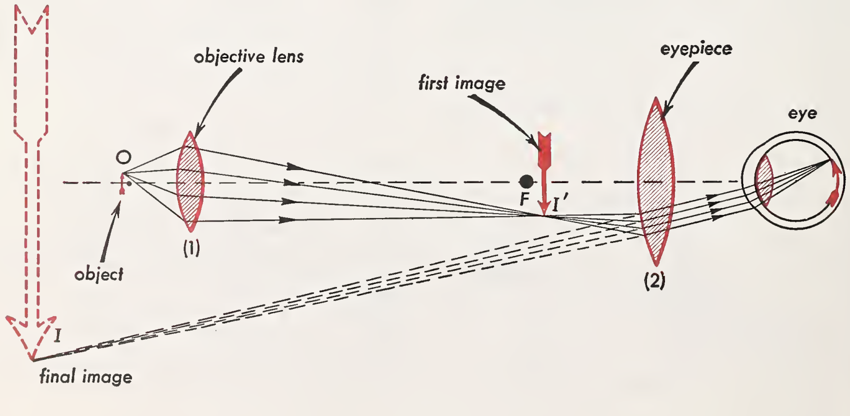
The simplest of microscopes is just a single converging lens used as a magnifier. As we have seen in Light, Lesson 13, the shorter the focal length of a lens the higher the magnification. It is not surprising to find, therefore, that small glass beads in the form of perfect spheres were the first really successful microscopes.

Lenses of this description were first used by the famous Dutch microscopist, Van Leeuwenhoek, when in 1674 he discovered and gave an accurate account of the red corpuscles in blood.

The compound microscope, which now exceeds by far the magnifying power of a single lens, was invented by Janssen in 1590.

Theory. The (compound) microscope Fig. A consists of two very short focus lenses, one called the ***objective*** and the other the

Fig. A. Lens and ray diagram of a compound microscope.



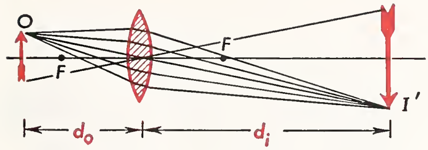


Fig. B. Showing the function of the objective lens of a microscope.

eyepiece. The objective lens is located close to the object **O** to be magnified and, as shown in Fig. B, forms a magnified image I' just in front of the eyepiece. Being another short focus lens, the eyepiece is used as a magnifier to produce a magnified virtual image at I. In other words, the real image I' of the first lens becomes the object for the second lens.

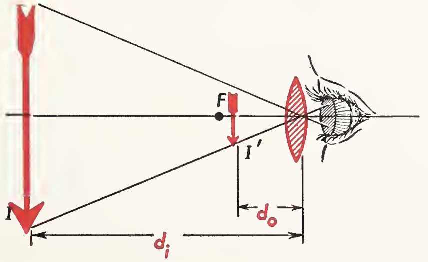
It is convenient to divide the principles of the microscope into two parts. The first part concerns the magnification produced by the objective lens. A diagram showing a short focus lens with its focal points **F**, as well as object and image, is shown in Fig. B.

Note how the object **O**, lying just outside the focal point at a distance d_o from the lens, forms a large image I' at a distance d_i. As we have seen in Light, Lesson 13, the magnification of such a lens is given by the relation

$$\boxed{M_O = \frac{d_i}{d_o}} \qquad (1)$$

The second part, as shown in Fig. C, is

Fig. C. Showing the function of the eyepiece of a microscope.



the eyepiece, with its object I' at a distance d_o from the lens and its image I as a virtual but magnified image. The magnification of such a lens is given by

$$\boxed{M_E = \frac{d_i}{d_o}} \qquad (2)$$

When the two are combined as shown in Fig. A, the over-all magnification is just the ratio of the final image size I to the original object size:

$$\boxed{M = \frac{I}{O}} \qquad (3)$$

and this is just the product of one magnification by the other:

$$\boxed{M = M_O \times M_E} \qquad (4)$$

For example, if the first lens made a 1-mm object appear 3 mm long, and the second lens made this 3-mm image look 12 mm long, $M_O = 3\times$, $M_E = 4\times$, and $M = 12\times$. The $\times$ is read as ***times.***

Apparatus. While very short focus lenses, each composed of several lens elements, are actually used as objectives and eyepieces in microscopes, the principles involved are best studied in this experiment by two thin lenses with focal lengths of from 8 to 12 cm. Both lenses may have the same or different focal lengths.

As an object, use a thin piece of sheet metal 3 to 4 in. square with a carefully drilled circular hole in the center. Drill the hole with a No. 32 gage drill followed with a $\frac{1}{8}$-in. reamer. Such a hole will be very round and have a diameter of 0.318 cm. An ordinary frosted lamp bulb behind this screen will give plenty of light. A white cardboard screen about 4 in. square is conveniently used to observe the image formed by the first lens, and a short centimeter rule is used for the final image measurement.

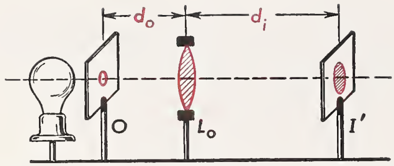


Fig. D. Optical arrangement for objective lens measurements.

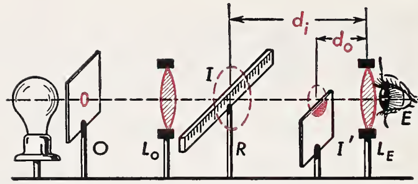


Fig. E. Optical arrangement with eyepiece lens and scale in position for measurements.

Object. *To investigate the possibility of producing high magnification with two short focus lenses.*

Procedure. Select either one of your two lenses and set it up with the object and image screens as shown in Fig. D. Adjust the lens L_o and screen position until the image is roughly five times as far from the lens as the object. Make the circular image as sharp as possible and measure d_o and d_i. Make a table of six columns, with headings as shown in Table 1, and record your readings in the first three columns.

Lower the image screen so that about two-thirds of the disk of light goes over the top. Set up the second lens L_E a little more than its focal length behind this screen as shown in Fig. E. With the centimeter scale *R* about 25 cm in front of the lens, and looking through the lens L_E, adjust its position until the magnified image *I* of the light disk *I′* can be seen superimposed on the centimeter scale.

This can best be done by looking into the second lens with one eye, and with the other eye focusing on the centimeter scale, adjust the position of L_E until the sharply defined circular light image seen through the lens is superimposed on the centimeter scale. A little practice will enable you to see the image *I* with one eye and the scale with the other.

Measure the object and image distances, as well as the final image size as seen on the centimeter scale, and record them in the last three columns of Table 1.

As a second trial, increase the object distance of the first lens by 1 cm and repeat all of the above steps and measurements. If time permits, increase the original object distance another 1 cm and repeat all steps.

Data. Suppose the above steps have been carried out for three separate trials and the data recorded as shown in Table 1.

Table 1. Recorded Data

Objective			Eyepiece		
O (cm)	d_o (cm)	d_i (cm)	d_o (cm)	d_i (cm)	*I* (cm)
.318	12.0	68.5	6.4	25.3	7.2
.318	13.0	47.1	6.2	24.5	4.5
.318	14.0	37.8	6.3	25.0	3.4

Calculations. Make a table of four columns with headings as shown in Table 2. Values for each of the columns are obtained by substituting the recorded data values into Eqs. (1), (2), (4), and (3), respectively.

Table 2. Calculated Results

M_O (×)	M_E (×)	M (×)	$\frac{I}{O}$

From your last trial measurements of d_o and d_i for the eyepiece, calculate the focal length of the eyepiece lens. Use this focal length to calculate the magnifying power

of the eyepiece by means of the formula

$$M = \frac{25}{f} + 1 \qquad (5)$$

and compare with the values in column 2.

Results. When the calculations are completed, each pair of over-all magnification values, as given in the last two columns, should be alike. Furthermore, since the image distance for the eyepiece was set at approximately 25 cm for all trials, M_E should be practically the same for all.

ELECTRICITY AND MAGNETISM

ELECTROMOTIVE FORCE OF A BATTERY CELL

To send an electric current through any electrical appliance, circuit, or conductor, one may use a generator or a battery.

In Electricity and Magnetism, Lesson 5, we will see that a battery is composed of two or more identical battery cells.

In Electricity and Magnetism, Lesson 3, we have seen that an individual cell of a battery is composed of three principal parts —a pair of electrodes, an electrolyte, and a cell container—and that a continuous supply of electrical charge to the cell terminals is attributed to a chemical action.

The Voltaic Cell. A voltaic cell as shown in Fig. F of Electricity and Magnetism, Lesson 3, contains all the essential elements of a battery cell. The voltmeter shown there is for measuring the potential difference between the cell terminals, and this we call $\mathcal{E}$, the ***electromotive force.***

The questions we wish to answer by the performance of this experiment are the following:

How does the emf depend upon the
1. *Electrolyte?*
2. *Electrodes?*
3. *Distance between electrodes?*
4. *Area of electrodes?*

How does the current depend upon the

5. *Distance between electrodes?*
6. *Area of electrodes?*

Apparatus. The apparatus to be used in this experiment consists of two clamps for suspending a pair of metal plates from the rim of a rectangular-shaped glass cell as shown in Fig. A. About 400 cm³ of dilute

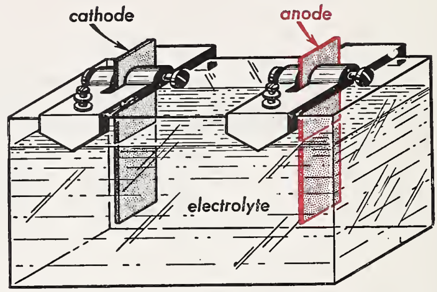


Fig. A. Cell assembly for the voltaic cell experiment.

sulfuric acid and 400 cm³ of dilute hydrochloric acid are needed as electrolytes. A D.C. voltmeter with a 2-volt or 3-volt full-scale reading should be used for measuring terminal emf, and a milliammeter is needed to measure current. A set of eight strips, composed of zinc, aluminum, iron, tin, nickel, lead, copper, and carbon, are suitable metals from which pairs of electrodes can be selected.

Because acids are corrosive, set all bottles and electrodes on paper toweling. Should you spill any acid on your clothing or on your person, notify the instructor at once. Each tiny drop of acid will make a hole in your clothing.

***Object.** To study the factors upon which the electromotive force of a cell, and the current supplied by a cell, depends.*

Procedure. Make a table of nine columns with headings as shown in Table 1 and leave space for three sets of trials as shown.

Pour dilute sulfuric acid into the glass cell until it is about two-thirds full. Insert a carbon electrode into one holder and a

zinc electrode into the other. Connect them to the voltmeter and insert them into the solution. Note the reading of the voltmeter and record the emf under zinc as shown in Table 1.

Note that the carbon electrode is the anode and should be connected to the plus terminal of the voltmeter.

Replace the zinc electrode with the aluminum electrode and record the emf as the first trial in column 4. Replace the aluminum by the iron, the tin, the nickel, and finally, the copper electrode, and record each corresponding voltmeter reading.

Replace the carbon anode by the copper and repeat the series of cathode metals starting with zinc. Record the emf of each pair of metals as shown in the second row of Table 1.

Pour out the sulfuric acid, thoroughly wash the cell and all electrodes with pure clean water, and fill the cell with dilute hydrochloric acid, HCl. With this new electrolyte, insert the carbon electrode as an anode and the zinc electrode as a cathode and measure the emf as before. Keeping the carbon anode, insert the other metals one after the other in their proper order and record the corresponding emf.

Remove the cell holders. Take a common nail and a copper penny, hold them in contact with the wire leads from the voltmeter, and dip their lower edges only into the electrolyte. Read and record the voltage. Replace the copper coin with a silver coin and again record the emf produced. Wash the coins thoroughly with water and dry before returning them to your pocket.

To find the answer to question 3, insert the zinc and carbon electrodes into the electrolyte and note the voltmeter reading as the plates are moved apart and then closely together.

To find the answer to question 4, note the voltmeter reading as the plates are raised slowly out of the liquid. Slowly lower the plates and note the voltmeter reading from the instant they simultaneously touch the liquid surface.

With the top of one electrode just touching the electrolyte, bring the other electrode up slowly and note the voltmeter reading as contact is made and broken intermittently. Record your findings.

To find the answer to questions 5 and 6 connect the milliammeter to the cell, using zinc and copper electrodes. Move the plates close together and then far apart, noting any possible change in current. Now lift the plates slowly out of the solution and note any change in current. Slowly insert the plates again, lowering them slowly while noting any current changes. (*Note:* As a rule an ammeter should not be connected directly across the terminals of a battery or cell. It is permissible in this experiment since the small plate areas will not permit large currents to be drawn.)

Data. If the above procedure has been carried out, the recorded data should have the appearance of that shown in Table 1.

Table 1. Recorded Data (volts)

Electrolyte	Anode	Zinc	Al	Fe	Sn	Ni	Pb	Cu
H_2SO_4	C	1.27	.61	.70	.76	.29	.70	.29
H_2SO_4	Cu	.92	.31	.40	.43	0	.38	—
HCl	C	1.21	1.10	.65	.77	.45	.73	.47

A nail and penny give .15 volts; a nail and dime give .35 volts.

As the plates are moved apart or close together, there is little or no change in the emf produced by the cell.

No change in emf is observed as the plates are raised or lowered. When the plates leave the electrolyte, the emf drops to zero; when they first make contact with the liquid surface, the emf immediately jumps to full voltage.

With the milliammeter connected and the plates moved apart, a small drop in current is noted. As they come closer together, the current rises slightly.

As the electrodes are raised, the current falls. When the submerged plate area is reduced to one-half, the current drops to one-half; when the submerged area is only one-quarter, the current is reduced to one-quarter. As the plates are lowered, the current rises steadily, reaching a maximum when the largest areas are submerged.

Conclusions. Answer the following questions:

1. Which combination of electrodes and electrolyte produce the largest emf?
2. Give brief answers to the six questions proposed at the beginning of this experiment.

Electricity and Magnetism | **Lesson 6**

SERIES CIRCUITS

The fundamental relation concerned with electrical circuits is Ohm's law:

$$\boxed{R = \frac{V}{I}} \qquad (1)$$

where R is the resistance of the circuit in ohms, V is the potential difference applied in volts, and I is the current in amperes.

Transforming this equation one obtains two other forms of Ohm's law:

$$\boxed{I = \frac{V}{R}} \qquad (2)$$

$$\boxed{V = IR} \qquad (3)$$

Theory. Part of the theory of series circuits was presented in Electricity and Magnetism, Lesson 5, where it was shown that the circuit resistance R is just the sum of the resistances of all the series elements:

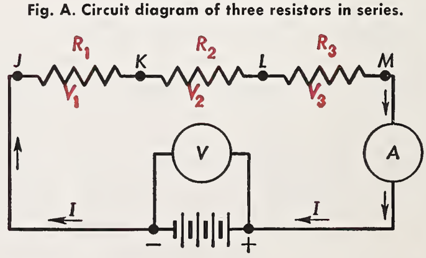
$$\boxed{R = R_1 + R_2 + R_3 + R_4 \ldots} \qquad (4)$$

A circuit diagram containing three resistors connected to a single battery is shown in Fig. A. Let us assume that $R_1 = 3\Omega$, $R_2 = 6\Omega$, and $R_3 = 15\Omega$, and that the battery maintains a potential difference $V = 60$ volts.

To calculate the current supplied by the battery, we first find the equivalent resistance of the entire series circuit. By Eq. (4)

$$R = 3 + 6 + 15 = 24\Omega$$

Fig. A. Circuit diagram of three resistors in series.



In other words, if the three resistors R_1, R_2, and R_3, are replaced by a single resistor R of 24Ω, the electron current supplied by the battery will be the same. To find this current we use Ohm's law, Eq. (2).

$$I = \frac{60 \text{ volts}}{24\Omega} = 2.5 \text{ amps}$$

This same electron current of 2.5 amps flows through R_1, R_2, and R_3, and can be measured as such with an ammeter connected as shown in Fig. A.

If the two leads of a voltmeter are connected to the two points J and K, the potential difference across R_1 is measured. Knowing the resistance of R_1 and the current I through it, one can calculate this potential difference by using Eq. (3).

$$V_1 = I_1 R_1$$
$$V_1 = 2.5 \text{ amps} \times 3\Omega = 7.5 \text{ volts}$$

Because the potential falls by 7.5 volts, from one side of the resistor to the other, this potential difference is commonly called the ***IR* drop.** In a similar way the *IR* drop across R_2 or R_3 can be measured by connecting the voltmeter to K and L, or L and M, or computed by means of Eq. (3):

$$V_2 = 2.5 \text{ amps} \times 6\Omega = 15 \text{ volts}$$
$$V_3 = 2.5 \text{ amps} \times 15\Omega = 37.5 \text{ volts}$$

If we find the sum of all the *IR* drops around the circuit, we obtain

$$7.5 + 15 + 37.5 = 60 \text{ volts}$$

This is known as Kirchhoff's law and is usually written

$$\boxed{V = V_1 + V_2 + V_3 + \ldots} \qquad (5)$$

Apparatus. It is the purpose of this experiment to determine the resistance of three separate resistors by measuring the voltage applied to them and the current passing through them in turn, and then to connect these resistors in series and find the *IR* drops across them.

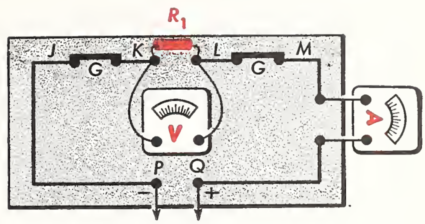


Fig. B. A connector board for studying resistors in series.

The apparatus consists of a set of three resistors—R_1, R_2, and R_3—of approximately 2Ω, 5Ω, and 10Ω; a connector board as shown in Fig. B; an appropriate voltmeter and ammeter; and a battery (preferably a storage battery of 12 volts).

Object. ***To study the laws of electrical resistors connected in series.***

Procedure. ***Part 1.*** Assign numbers to each of your resistors in the order of increasing resistance. Connect R_1 into the circuit as shown in Fig. B. Connect the battery to the lower binding posts marked + and −, and the ammeter A in series as shown. Read the ammeter current I in amperes and record in a table of three columns with headings as shown in Table 1.

Touch the two voltmeter leads to the two ends of R_1 as shown and record the voltmeter reading as V in Table 1.

Replace R_1 by the second resistor R_2 and repeat voltmeter and ammeter measurements as before. Record as indicated in Table 1. Repeat these measurements for R_3 and record.

Part 2. Remove jumper **G** between J and K, and connect R_1 and R_2 as shown in Fig. C. When the battery is connected, read the ammeter and record the current as I. See Table 2. Touch the voltmeter leads to P and Q, and record the voltage as V. Next touch the same leads to J and K, and record

as V_1. Finally, touch the voltmeter leads to K and L, and record as V_2. These two readings represent the measured IR drop across each resistor, and their sum should be equal to V.

***Part* 3.** Remove jumper **G** between L and M, and connect R_3 as shown in Fig. D. When the battery has been connected, read the ammeter and record the current as I. See Table 3. Touch the voltmeter leads to **P** and **Q**, and record the voltage as V. Next touch the same leads to J and K, then K and L, and finally L and M, and record the readings as V_1, V_2, and V_3, respectively.

Data. Assume the above steps have been properly carried out and the meter readings recorded as follows. For Part 1, we have Table 1.

Table 1. Recorded Data

R (number)	V (volts)	I (amps)
R_1	12.2	5.80
R_2	12.4	2.90
R_3	12.5	0.85

Recorded data for Part 2 and Part 3, respectively.

Table 2

I = 2 amps
V = 12.6 volts
V_1 = 4.1 volts
V_2 = 8.6 volts

Table 3

I = 0.6 amps
V = 12.6 volts
V_1 = 1.3 volts
V_2 = 2.6 volts
V_3 = 8.8 volts

Calculations. ***Part* 1.** Using the data recorded in Part 1, and Ohm's law, calculate the resistance of R_1, R_2, and R_3.

***Part* 2.** Using R_1 and R_2 found in Part 1, and the total current I measured in Part 2, find IR_1 and IR_2. Compare these two IR drops with the measured V_1 and V_2 from Part 2. Add V_1 and V_2, and compare with V. This is a test of Kirchhoff's law, Eq. (4).

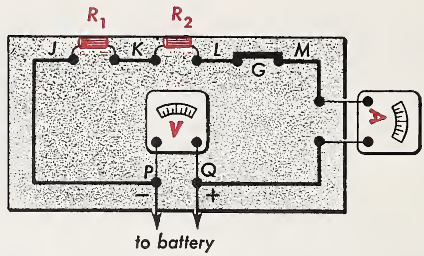


Fig. C. A connector board with two resistors in series.

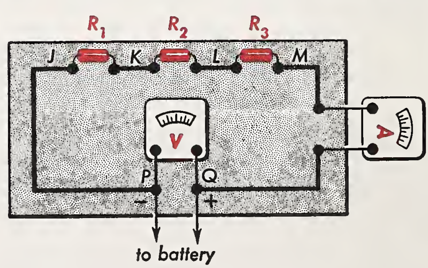
***Part* 3.** Using R_1, R_2, and R_3 found in Part 1, and I from Part 3, calculate IR_1, IR_2, and IR_3. Compare these with the measured V_1, V_2, and V_3, respectively.

Add V_1, V_2, and V_3, and compare with the measured V. This is a test of Kirchhoff's law, Eq. (4).

Results. List all your calculated data for Parts 2 and 3 in one column and the comparison measurements directly behind them in a second column.

Conclusions. What conclusions can you draw from this experiment?

Fig. D. A connector board with three resistors in series.



Electricity and Magnetism | Lesson 9

PARALLEL RESISTANCES

Because of the numerous uses of electrical devices involving resistors in parallel it is important to every physicist that he thoroughly understand their electrical characteristics. It is for this reason that we propose to select several resistors, determine their respective resistances, connect them in parallel combinations, and measure the currents and voltages through and across each one.

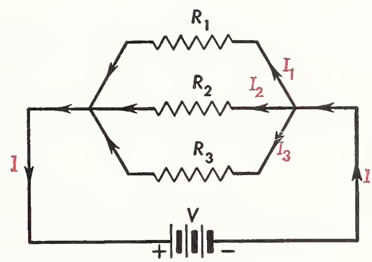


Fig. A. Circuit with three resistors in parallel.

Theory. The fundamental principles concerning all electric circuits are given in five basic equations. They are Ohm's law,

$$\boxed{I = \frac{V}{R}} \qquad (1)$$

the law of series resistances,

$$\boxed{R = R_1 + R_2 + R_3 + \ldots} \qquad (2)$$

the law of parallel resistances,

$$\boxed{\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots} \qquad (3)$$

and Kirchhoff's two laws,

$$\boxed{V = V_1 + V_2 + V_3 + \ldots} \qquad (4)$$

$$\boxed{I = I_1 + I_2 + I_3 + \ldots} \qquad (5)$$

For a circuit involving parallel resistors only, see Fig. A. We may employ Eq. (2) to find the equivalent resistance R of the circuit, and upon substitution in Eq. (1), find the total current I flowing through the circuit. See Electricity and Magnetism, Lesson 7.

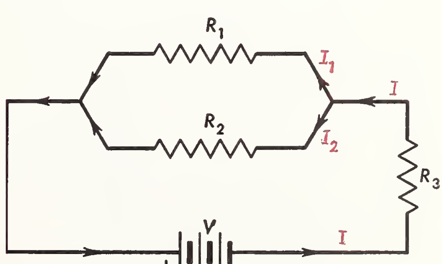
To find how the current divides and flows through the separate resistors, apply Ohm's law to each resistor separately.

$$\boxed{I_1 = \frac{V}{R_1}, \quad I_2 = \frac{V}{R_2}, \quad I_3 = \frac{V}{R_3}} \qquad (6)$$

Kirchhoff's law, which says that the sum of the currents flowing into any junction is equal to the sum of the currents flowing out, Eq. (5), can then be applied as a check upon the results.

A circuit involving a combination of series and parallel resistors will also be studied in this experiment. As shown in Fig. B, this particular circuit is composed of two resistors R_1 and R_2 in parallel, and this

Fig. B. A series-parallel combination.



combination in series with a third resistor R_3.

If we apply Eq. (3) to R_1 and R_2 alone, we find

$$\frac{1}{R'} = \frac{1}{R_1} + \frac{1}{R_2} \tag{7}$$

where R' is the equivalent resistance of the parallel combination only. Since this part of the circuit is in series with R_3, the law of series resistances, Eq. (2), is applied and we find

$$R = R' + R_3 \tag{8}$$

where R is the equivalent resistance of the entire circuit. Ohm's law can then be applied to this R and to the applied potential difference V to obtain the total current I.

To find how the current divides at the center junction, the potential difference across the parallel circuit is calculated from Ohm's law.

$$V' = IR' \tag{9}$$

Then with this value of V' as the potential difference between the ends of R_1 as well as R_2, Ohm's law can be applied to each resistance separately.

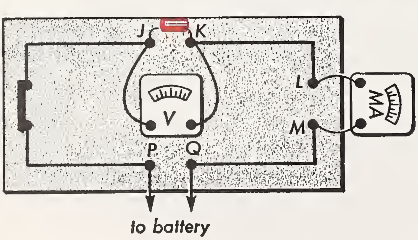
$$I_1 = \frac{V'}{R_1}$$

and

$$I_2 = \frac{V'}{R_2} \tag{10}$$

Apparatus. The apparatus in this experiment consists of three separate connector boards containing brass connector

Fig. C. A connector board for a laboratory experiment.



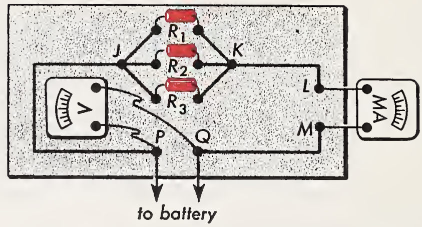


Fig. D. A connector board for parallel resistors.

strips with binding posts as shown in Figs. C, D, and E. A 12-volt storage battery, a d.-c. voltmeter, a d.-c. milliammeter, and a set of three resistors with resistances—R_1, R_2, and R_3—of approximately 500, 300, and 150 ohms, respectively, are used.

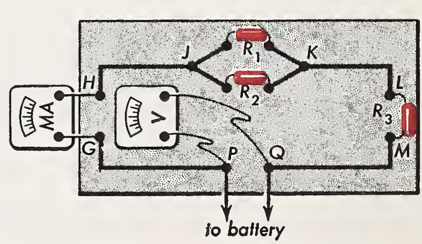
Object. ***To study the principles of electric circuits involving resistors connected in parallel.***

Procedure. ***Part 1.*** Assemble the parts for the first connector board and make all connections as shown in Fig. C. With R_1 connected between the two binding posts at the top of the board, read the voltage across $\boldsymbol{PQ}$ or $\boldsymbol{JK}$ and the current through $\boldsymbol{LM}$. Record these in a table of three columns with headings as shown in Table 1.

Replace R_1 by R_2 and repeat these measurements. Record the current and voltage as trial 2.

Replace R_2 by R_3 and again record V and I in Table 1.

Fig. E. Connector board for series-parallel combination of resistors.



***Part* 2.** Assemble the parts for the second connector board and make all connections as shown in Fig. D. With all three resistors in place, read the battery voltage **V** and the total current I, and record them as shown in Table 2.

Disconnect the milliammeter and put a jumper connector across **LM**. Remove the jumper from **K** to R_1 and connect the milliammeter to these points. Read and record the current as I_1.

Replace the jumper to R_1 and remove the jumper from **K** to R_2 and connect the milliammeter there. Read and record the current as I_2.

Repeat this procedure to find I_3.

***Part* 3.** Assemble all parts for the third connector board and make all connections as shown in Fig. E. With all three resistors in the positions shown, read and record the battery voltage **V** and total current I. See Table 3.

With a jumper across **GH** and the jumper from **K** to R_1 removed, connect the milliammeter and measure the current through R_1. Record this current as I_1. Repeat this procedure and find the current I_2 flowing through R_2.

With all connections as shown in Fig. E, move the voltmeter connections from **PQ** to **LM** and record the voltage as V_3. Move the voltmeter connections to **JK** and record the voltage as V_1 as well as V_2.

Data. We will assume that all measurements have been made and the data recorded for Parts 1, 2, and 3 in Tables 1, 2, and 3, respectively.

Table 1. Recorded Data

R	V (volts)	I (amps)
1	12.6	.032
2	12.6	.044
3	12.6	.081

Table 2. Recorded Data

V	I	I_1	I_2	I_3
12.6	.155	.033	.044	.081

Table 3. Recorded Data

V	V_1	V_2	V_3
12.6	6.5	6.5	6.1

I	I_1	I_2
.039	.016	.023

Calculations. ***Part* 1.** Use Ohm's law and calculate values for R_1, R_2, and R_3. List the results in your final report as Part 1.

***Part* 2.** Using the measured **V** and I in Table 2, use Ohm's law to find the circuit resistance **R**. Compare this **R** with the combination resistance **R** calculated from Eq. (3) and the values of R_1, R_2, and R_3 from Table 1.

Compute values of V/I_1, V/I_2, and V/I_3 from Table 2, and compare them with R_1, R_2, and R_3, respectively, from Part 1. For easy comparison, list these values as pairs in your final report.

***Part* 3.** Using the values of I_1, I_2, and I from Part 3, and R_1, R_2, and R_3 from Part 1, calculate I_1R_1, I_2R_2, and IR_3. List these results on your final report and give the values of V_1, V_2, and V_3 as measured in Part 3 beside them.

From Part 3 data only, compute V_1/I_1, V_2/I_2, and V_3/I.

Compare these with R_1, R_2, and R_3 from Part 1.

Finally, compute R' from the values of

R_1 and R_2 in Part 1, using Eq. (7). Use Eq. (8) to find R. Compare this resultant R with V/I as found from the data in Table 3.

Conclusions. See if you can write down, from memory, the five basic equations for electrical circuits. If you can follow and understand the principles of this experiment, you have accomplished a great deal, and you will be able to solve many of the most complicated as well as the simplest problems of electric circuits.

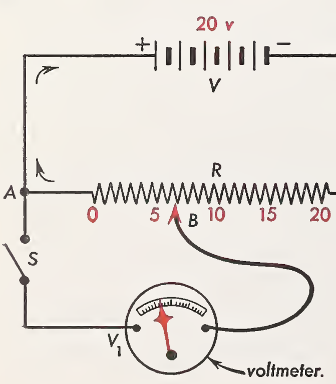
Electricity and Magnetism | **Lesson 11**

THE POTENTIAL DIVIDER

The potential divider is an electrical circuit constructed around a variable resistor, or rheostat, with a sliding contact. When such a device is connected to a battery as shown in Fig. A, the sliding contact makes it possible to obtain any desired potential difference from zero up to the full voltage V of the battery.

Suppose, as shown in Fig. A, that a battery supplies 20 volts to the extreme ends of a resistance wire AC, and a voltmeter V is connected to one end A and to a sliding contact B. When the slider B is at A, the voltmeter will read zero, but as it moves down toward C, the reading will steadily rise. One-quarter of the way to C the voltmeter will read 5 volts; half-way, 10 volts; three-quarters of the way, 15 volts; and finally at C it will read 20 volts. As a general rule the potential difference is directly proportional to the length of the resistance wire between A and B.

Fig. A. Potentiometer circuit for obtaining variable voltage.



As a sample calculation let the total resistance A to C in Fig. A be 100 ohms. By Ohm's law the current through AC will be

$$I = \frac{20 \text{ volts}}{100\Omega} = 0.2 \text{ amp}$$

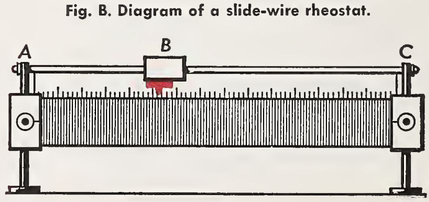
Let B be located three-quarters of the way to C so that the resistance A to B is $100 \times \frac{3}{4}$, or 75 ohms. The IR drop across this portion is, therefore,

$$IR = 0.2 \times 75 = 15 \text{ volts}$$

as also shown by the voltmeter.

Apparatus. A slide-wire rheostat of a conventional type is shown in Fig. B. This is a porcelain tube about 2 in. in diameter

Fig. B. Diagram of a slide-wire rheostat.



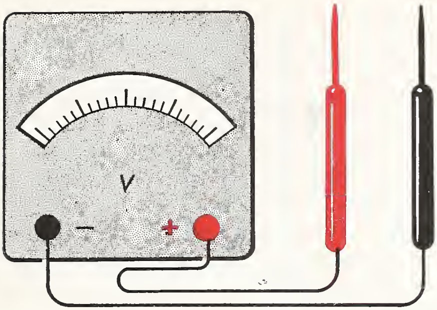


Fig. C. Voltmeter with pointed probes for voltage-divider experiment.

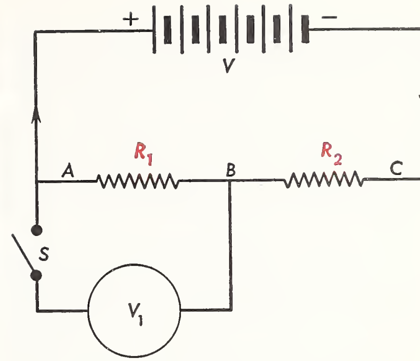


Fig. D. Circuit diagram for potential divider.

and 12 in. long, with a long, uniform resistance wire wrapped around it in the form of a coil of only one layer.

The slider at the top is mounted on a conducting rod and by sliding it along, it makes contact with the resistance wire at any desired position. If desired, a short section of a meter stick can be mounted close to the slider, thus making it a simple matter to determine the distance from either end of the rheostat to any contact point.

Because most sliding contacts are usually quite broad, thereby making their exact contact point difficult to determine with precision, the slider will not be used.

In its place two pointed probes with insulated handles, connected to a voltmeter as shown in Fig. C, are used to "pinpoint" the voltmeter contacts.

If a 110-volt to 120-volt, direct-current line, or battery, is available for use, the rheostat should have a resistance of 1000 Ω to 3000 Ω. If a 12-volt storage battery is used, a 100-Ω to 300-Ω rheostat is conveniently employed. In either case a suitable voltmeter capable of measuring the maximum available voltage is required.

Theory. In effect, the sliding contact of a rheostat divides the total resistance R into two parts R_1 and R_2. The circuit may therefore be drawn as shown in Fig. D.

The current I flowing through both resistances (neglecting the voltmeter) is given by Ohm's law:

$$V = IR \tag{1}$$

where

$$R = R_1 + R_2 \tag{2}$$

The potential difference between points A and B is just the IR drop across R_1.

$$V_1 = IR_1 \tag{3}$$

If we divide Eq. (3) by Eq. (1), we obtain

$$\frac{V_1}{V} = \frac{IR_1}{IR}$$

Canceling I, we find

$$V_1 = \frac{V}{R} R_1 \tag{4}$$

Since V and R do not change in value, V/R is constant. This means that V_1 is directly proportional to R_1. Furthermore, since the resistance of a uniform wire is proportional to its length L, we can write

$$\boxed{V_1 = kL} \tag{5}$$

Object. ***To study the principles of an electrical circuit called a potential divider.***

Procedure. Connect the full line or battery voltage V to the rheostat ends A and

C. With one of the voltmeter probes in one hand touch the point to position ***A*** at the end of the resistance wire, and with the other probe touch a point 5 cm to the right. Record the probe positions ***A*** and ***B*** as well as the voltmeter reading V_1 in a table of three columns with headings as shown in Table 1.

With probe ***A*** still at the end, move probe ***B*** 5 cm more to the right and record the voltmeter reading. Repeat this process, moving probe ***B*** 5 cm at a time and recording the position and voltage with each change.

When the end **C** has been reached, move probe ***A*** 5 cm from the end of the resistance wire and probe ***B*** to a position 5 cm to its right. Record these positions as well as the voltage. Move probe ***A*** to a point 10 cm to the right of the end and probe ***B*** 5 cm farther along, and record.

Finally, move probe ***A*** to any position along the rheostat and probe ***B*** to a position just 5 cm away, and record the voltage.

If time and equipment are available, use another source of voltage and another suitable rheostat and voltmeter, and repeat the experiment.

Data. We will assume that the above procedure has been carried out and the data recorded as shown in Table 1.

Calculations. The calculations required in this experiment consist first of taking the difference between each pair of ***A*** and ***B*** distances recorded in Table 1 and listing them along with V_1. For this purpose, make a table of three columns with headings as shown in Table 2. The first trial results are included for comparison purposes.

Divide each value of V_1 by its corresponding length L to obtain the values in column 3.

Table 1. Recorded Data

A (cm)	B (cm)	V_1 (volts)
1.0	6.0	21.5
1.0	11.0	43.0
1.0	16.0	65.0
1.0	21.0	86.5
1.0	26.0	108
6.0	11.0	22.0
11.0	16.0	21.5
18.0	23.0	21.5

Table 2. Calculated Results

V_1 (volts)	L (cm)	V_1/L (volts/cm)
21.5	5.0	4.30

Results. Plot a graph to show the relation between the resistance wire length L and the potential difference V_1. Plot V_1 vertically and label the scale 0, 10, 20, 30, . . . 120 volts. Plot L horizontally and label the scale 0, 5, 10, 15, 20, and 25 cm.

Calculate the average of the V_1/L values in column 3.

Using this average value, calculate the potential difference between two points 12.5 cm apart on the rheostat.

Electricity and Magnetism | **Lesson 14**

WHEATSTONE BRIDGE

The Wheatstone bridge is an electrical circuit used quite widely to determine with high precision the electrical resistance of any wire or appliance. Such a circuit involves several electrical resistors and may take any one of several forms.

Theory. There are several factors that determine the electric resistance of any wire: (1) the material of which it is composed, (2) the size of the wire, and (3) its temperature. If the length of a wire is doubled, its resistance is likewise doubled; if the cross-sectional area is doubled, the resistance is halved. In more general terms, the resistance of a wire is proportional to its length and inversely proportional to its cross-sectional area. Symbolically,

$$R = \rho \frac{L}{A} \tag{1}$$

where **R** is the resistance, **L** the length, **A** the cross-sectional area, and ρ the ***resistivity*** of the material in question. Resistivity is defined as the resistance of a wire 1 m long and 1 m² in cross section. Values of this constant are given for several common metals in Table 1. The smaller the constant ρ, the better is the substance as a conductor.

Table 1. Resistivity of Metals in Ohm Meters (at 20°C)

nichrome (resistance)	$\rho = 1.00 \times 10^{-8}$
aluminum	$\rho = 3.2 \times 10^{-8}$
bismuth	$\rho = 119 \times 10^{-8}$
copper	$\rho = 1.69 \times 10^{-8}$
iron	$\rho = 10.0 \times 10^{-8}$
mercury	$\rho = 94.1 \times 10^{-8}$
silver	$\rho = 1.59 \times 10^{-8}$
tungsten	$\rho = 5.5 \times 10^{-8}$
platinum	$\rho = 10 \times 10^{-8}$

To find the resistance of any sized wire made of one of these metals, the value of ρ is inserted in Eq. (1) along with the length and cross-sectional area, and the value of **R** is calculated. To illustrate the method, consider the following:

Example. Find the resistance of a copper wire 1 sq mm in cross section and 300 m long.

Solution. If we use Eq. (1) and remember that there are 1000 mm in 1 m, we find that

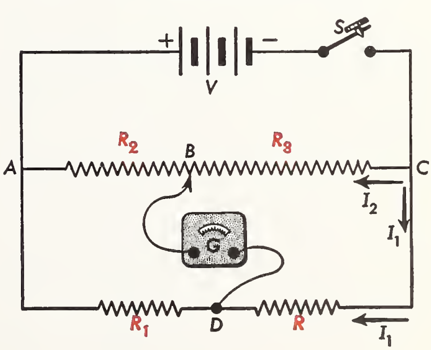
$$R = 1.69 \times 10^{-8} \frac{300 \text{ m}}{1 \times 10^{-6} \text{ m}^2} = 5.07 \text{ ohms}$$

If ρ is the unknown quantity to be determined by experiment, Eq. (1) can be transformed to give

$$\boxed{\rho = \frac{RA}{L}} \tag{2}$$

Circuitwise the Wheatstone bridge is shown in Fig. A. A battery of but a few volts

Fig. A. The circuit of the Wheatstone bridge.



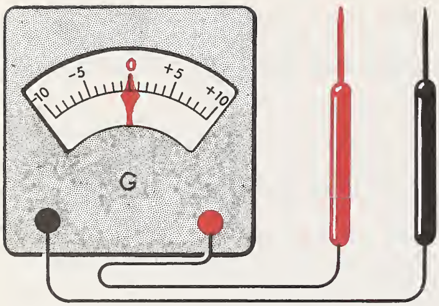


Fig. B. Galvanometer with two insulated probes.

is connected in parallel with a circuit involving a resistance wire with a sliding contact and two other resistors R and R_1. A switch S is connected into the battery circuit for applying the potential wherever desired, and a galvanometer is connected to the sliding contactor and the junction between R and R_1.

A galvanometer is a sensitive current-reading instrument, with the zero point at the center of its scale as shown in Fig. B. If the current flows one way through the instrument, the needle deflects to the right. If the current flows in the other direction, the needle deflects to the left. If the probes make contact at two points in a circuit and the needle shows no current one way or the other, those two points are at the same potential. If there were a difference of potential, a current would flow.

Of the different resistors shown in Fig. A, R represents the unknown resistance to be determined, R_1 a precision known resistance, and R_2 and R_3 the sections of a uniform slide wire.

When the switch is closed, a current I_2 flows through the slide wire and a current I_1 through R and R_1. If the sliding contact is moved along until a point B is reached where the galvanometer shows no current, the points B and D will be at exactly the same potential.

Under these balanced conditions the potential difference between A and B will be the same as between A and D, and the potential difference between C and B will be the same as between C and D. Since these differences in potential are given by the respective IR drops, we can write

$$I_1R_1 = I_2R_2$$

and

$$I_1R = I_2R_3$$

Since equals divided by equals give equals, we find

$$\frac{I_1R}{I_1R_1} = \frac{I_2R_3}{I_2R_2}$$

Canceling, we obtain

$$\frac{R}{R_1} = \frac{R_3}{R_2}$$

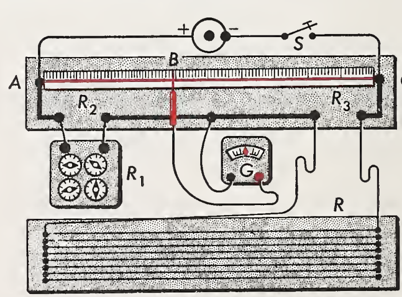
Solving for the unknown resistance R, we have

$$\boxed{R = R_1\frac{R_3}{R_2}} \tag{3}$$

Since the resistance of a uniform wire is proportional to its length, we can use the measured lengths of the slide wire between A and B and between B and C, and substitute these for R_2 and R_3 in Eq. (3).

Apparatus. A convenient Wheatstone bridge circuit board is shown in Fig. C. R_1 is a dial type of standard resistance box. By

Fig. C. A Wheatstone bridge circuit board and all connections to auxiliary equipment.



turning the dials the value of R_1 in ohms can be set at any value in 1-Ω steps up to 10,000 Ω.

A convenient set of unknown resistors is obtained by stretching several strands of standard gage copper, iron, or any commercial make of resistance wire, between insulated pegs or binding posts on a board. Several such strands, each one meter long, are shown in Fig. C.

Object. ***To use a Wheatstone bridge circuit to find the resistance of several resistors.***

Procedure. If the diameters or cross-sectional areas of the resistance wires of R are not already known, measure their diameters with a micrometer, compute their areas in m², and record them in a table of six columns. See Table 2. If the gage numbers are known, their areas can be looked up in standard tables.

When the bridge connections have been made as shown in Fig. C, the connecting wires for the first trial should include only the first 1-m strand of resistance wire. Turn the dials of R_1 to include about 100 Ω. Momentarily close the switch S and touch the slide wire at the 50-cm mark with the probe tip B.

If the galavanometer shows a deflection (and it probably will), move the probe to the left. If the deflection decreases, move it farther to the left; if the deflection increases, move it to the right. If when you find the zero current position, the probe is outside the 25-cm to 75-cm range, alter the box resistance R_1 and balance again. Try to make the ***null position*** come as close to the center as possible.

When the null position has been located, record the wire length L, the box resistance R_1, and the slide wire resistances R_2 and R_3 as shown in Table 2.

Connect two 1-m lengths of the same resistance wire in series and connect them into the bridge circuit as R. Balance the bridge again, trying to make the balance position of the probe B somewhere near the middle of the slide wire, and record your readings in Table 2.

Repeat all the above steps for each of your unknown resistance wires. If several strands of the same wire are available, use 3-, 4-, and 5-m lengths in series as your third, fourth, and fifth trials.

Data. Let us suppose that the above procedure has been carried out for eight trials and the data have been recorded as shown in Table 2. The wire used for this particular data was standard gage, and its cross-sectional area is assumed to be as listed in standard gage tables. (See *Handbook of Chemistry and Physics,* Chemical Rubber Publishing Co.)

Table 2. Recorded Data

Metal	A (m²)	L (m)	R_1 (Ω)	R_2 (cm)	R_3 (cm)
nichrome	8.10×10^{-8}	1.0	10.0	45.2	54.8
nichrome	8.10×10^{-8}	2.0	20.0	44.4	55.6
nichrome	8.10×10^{-8}	3.0	40.0	51.8	48.2
nichrome	8.10×10^{-8}	4.0	50.0	50.3	49.7
iron	8.10×10^{-8}	1.0	2.0	61.9	38.1
iron	32.6×10^{-8}	1.0	1.0	76.3	23.7
copper	1.27×10^{-8}	1.0	1.0	42.6	57.4
copper	8.10×10^{-8}	1.0	1.0	82.5	17.5

Calculations. Make a table of four columns for your calculations and use headings shown in Table 3. The first trial computations have been included for comparison purposes.

Table 3. Calculated Results

R (Ω)	RA (Ω × m²)	ρ (Ω × m)	ρ (accepted)
12.1	98.0×10^{-8}	98.0×10^{-8}	100×10^{-8}

The values of R in the first column are found from Eq. (3). Column 3 is obtained by use of Eq. (2). The accepted values of ρ are obtained from Table 1.

Results. Calculate an average value of ρ for each metal and compare the results with accepted values.

Electricity and Magnetism | **Lesson 16**

ELECTRICAL EQUIVALENT OF HEAT

It is the purpose of this experiment to convert a measured amount of electrical energy into heat and then, by measuring the amount of heat produced, to attempt to check the validity of ***Joule's law***. Joule's law is just one of the many forms of the more general law of the conservation of energy, and involves the ***electrical equivalent of heat.***

Theory. Consider the two terminals of a battery as shown in Fig. A and the mechanical work that would be required to move a negative charge from the (+) terminal to the (−) terminal. The amount of work done per unit charge in carrying any charge Q from one terminal to the other is called the ***difference of potential***. Symbolically,

$$V = \frac{E}{Q} \tag{1}$$

where V is in volts, E is in joules, and Q is in coulombs.

If, instead of carrying a charge from one terminal to the other and thereby doing work, we connect the two terminals with a conductor, a current I will flow and the battery will be doing work for us in creating heat. By definition, ***the current I is defined as the amount of charge Q flowing per second of time.***

$$I = \frac{Q}{t} \tag{2}$$

If we solve this equation for Q

$$Q = It$$

and substitute It for Q in Eq. (1), we obtain

$$V = \frac{E}{It} \tag{3}$$

Upon transposing, we find

$$\boxed{E = VIt} \tag{4}$$

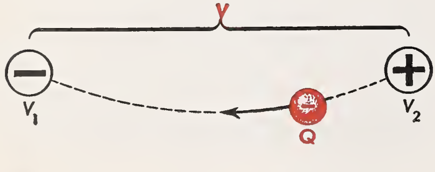
joules = volts × amperes × seconds

Since the electrical energy expended is transformed into heat, the joules of energy E should be expressed in calories of energy H. As shown in Electricity and Magnetism, Lesson 15, E and H are proportional to each other and their ratio is given by a constant J, called the ***electrical equivalent of heat.***

$$J = \frac{E}{H} = 4.18\ \frac{\text{joules}}{\text{cal}} \tag{5}$$

and is exactly the same as the ***mechanical equivalent of heat.***

Fig. A. The work done per unit charge in carrying any charge Q from one terminal to the other is called the difference of potential V.



By inverting this equation, we obtain

$$\frac{1}{J} = \frac{H}{E} = 0.239 \frac{\text{calorie}}{\text{joule}} \tag{6}$$

To measure the electrical energy consumed by any circuit we can measure the current I with an ammeter, the voltage V with a voltmeter, and the time t with a clock.

To measure the heat produced we make use of the methods of calorimetry as presented in previous lessons. The heat gained by any object is given by

$$\boxed{H = mc(T_2 - T_1)} \tag{7}$$

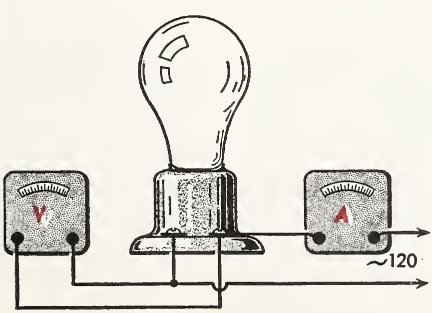
where m is the mass of a body, c is its specific heat, and $T_2 - T_1$ is its rise in temperature.

Apparatus. A regular 60-watt tungsten filament light bulb, mounted in a screw-base porcelain socket, is used to convert electrical energy into heat energy. The electrical energy input is measured by means of a voltmeter and ammeter as shown in the circuit diagram of Fig. B.

The heat developed is measured with a calorimeter as shown in Fig. C. Any wind-up clock or electric clock with a sweep second hand will serve for determining the rate of rise of the temperature of the water.

As the experiment is being performed, the heat developed by the light bulb goes to heat up the water, the calorimeter cup, and the bulb. To find H we must, therefore, account for the heat that goes into these three objects.

Fig. B. Voltmeter and ammeter connections for lamp bulb.

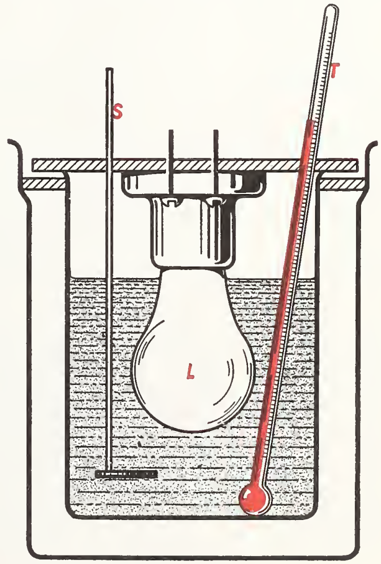


***Object.** To measure the heat produced in a current-carrying resistor and determine the electrical equivalent of heat.*

Procedure. Weigh the inner calorimeter cup and then the light bulb, and record their masses in grams as m_c and m_b. See Table 1. Look up the specific heats of glass and aluminum, and record these in Table 1 as the specific heats for the bulb and calorimeter cup, respectively.

Fill the cup about half-full of cold water and insert the light bulb to see how high the water level rises. Sufficient water should be added to bring the level close to but not touching any metal parts of the socket. Remove and dry the bulb, and weigh the cup and water. Record as $m_c + m_w$ in Table 1.

Fig. C. Mounting of light bulb in a calorimeter.



Read the thermometer and record the room temperature T.

Assemble the calorimeter and insert the bulb, stirrer, and thermometer as shown in Fig. C. Make a table of two columns on your data sheet and label them with headings as shown in Table 2.

Turn on the light bulb and gently stir the water. As the sweep hand of the clock passes the vertical position, read and record the water temperature. Watch the clock, and at each succeeding 30 seconds read and record the water temperature as shown in Table 2.

Continue to stir and take readings. When the water temperature reaches 3°C above the room temperature, make your last reading on the minute. Read and record the ammeter and voltmeter readings.

Table 2. Recorded Data

t (min)	T (°C)
0	21.2
0.5	21.8
1.0	22.5
1.5	23.2
2.0	23.8
2.5	24.4
3.0	25.0
3.5	25.7
4.0	26.3
4.5	26.9
5.0	27.5
5.5	28.0
6.0	28.6

Data. Let us assume that the above steps have been carried out and you have recorded the data as shown in Tables 1 and 2.

Table 1. Recorded Data

applied voltage	$V = 116$ volts
applied current	$I = 0.52$ amp
mass of cup	$m_c = 195$ gm
cup of water	$m_c + m_w = 806$ gm
mass of bulb	$m_b = 50.8$ gm
sp ht of bulb	$c_b = 0.16$
sp ht of cup	$c_c = 0.22$
room temp	$T = 25.0$°C
mass of water	$m_w = ?$
rise in T	$T_2 - T_1 = ?$
time interval	$t = ?$

Calculations. To find the last two values in Table 1, plot a graph of the data recorded in Table 2. The vertical scale for T should be labeled 20, 22, 24, . . . 30°C, and the horizontal scale for t should be labeled 0, 1, 2, 3, 4, 5, and 6 min.

Draw a smooth curve through your plotted points and then draw a tangent to this curve at the point of room temperature. Since this tangent represents the true rate of temperature rise, use it to find the true rise for a period of 5 min. Record these as $T_2 - T_1$ and t in Table 1.

Find the electrical energy input for a period of 5 minutes by substitution in Eq. (4).

Find the heat energy that went into (a) the water, (b) the calorimeter cup, and (c) the lamp bulb by using Eq. (7).

Take the ratio of E to H and find J.

Take the ratio of H to E and find $1/J$.

Compare these last two ratios with the accepted values of J and $1/J$ given in Eqs. (5) and (6).

Find your percentage error.

Electricity and Magnetism | **Lesson 19**

A STUDY OF MOTORS

This lesson is a laboratory experiment on the principles of the electric motor. In essence it is a descriptive type of experiment that requires careful observations but no quantitative measurements.

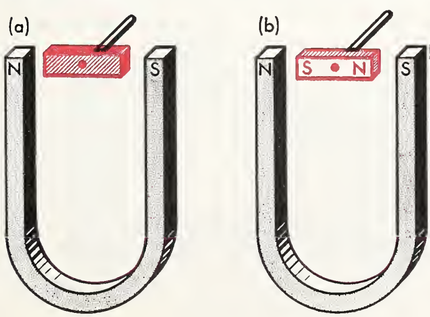
Theory. To introduce the principles of the motor we will find it convenient to begin with a U-shaped magnet and a short bar of soft iron mounted free to turn between its poles as shown in Fig. A(a). If one spins the iron bar, it will slow down, oscillate, and finally come to rest in the position shown, with either end to the right or left.

If, on the other hand, a small permanent magnet is mounted free to spin in the same way, it will always come to rest in one position only, with opposite poles adjacent, as shown in diagram (b).

Let us now consider the magnetic fields involved in the first demonstration. The field between the poles of the magnet is shown in Fig. B. When the soft iron bar is interposed, as in Fig. C, the lines of force not only change their shape but they induce **N** and **S** polar regions in the iron. Just as a copper wire is a good conductor of electron currents, so soft iron acts as though it were a good conductor of magnetic lines of force.

This property of a medium to conduct

Fig. A. A soft iron bar, or a magnet, lines up with the magnetic field.



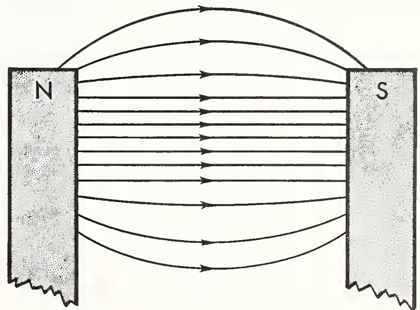
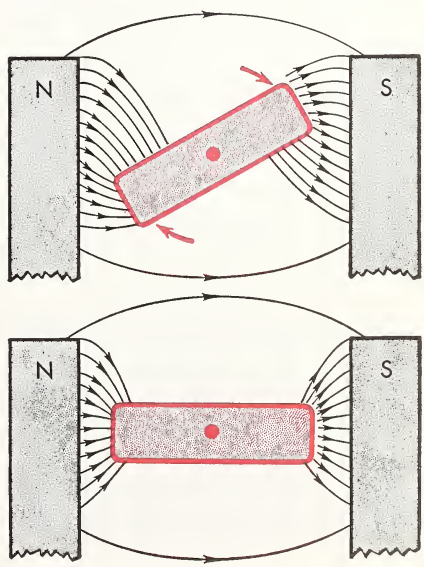


Fig. B. The magnetic field between the two poles of a U-shaped magnet.

Fig. C. A soft iron bar in the field of a permanent magnet.



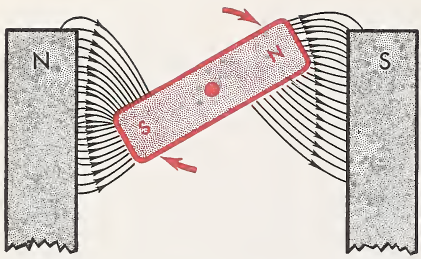


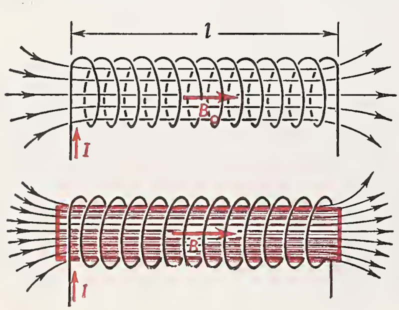
Fig. D. Permanent magnet in the field of another permanent magnet.

lines of force is called ***reluctance,*** and it is analogous to electrical resistance for currents. Air has a high reluctance, while soft iron has a low reluctance. It is not to be assumed by this analogy that magnetic lines of force constitute a flow of any kind. The arrows simply indicate the direction a compass needle would point if located there.

In the case of the permanent bar magnet, the bar again bridges the air gap by a "good conductor," i.e., one of low reluctance. Because of the strong interacting fields, the permanent bar magnet experiences a stronger force tending to line it up with the magnetic field of the U-shaped magnet as shown in Fig. D.

The Armature. We have seen in Electricity and Magnetism, Lesson 18, how the magnetic induction B_o at the center of a solenoid is given by

Fig. E. An iron core greatly strengthens the magnetic induction in a solenoid.



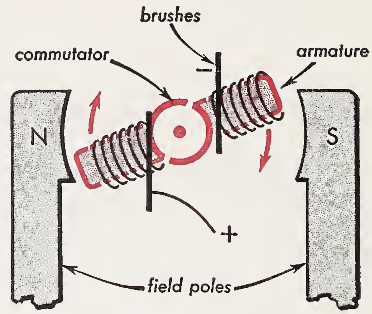


Fig. F. Principal parts of a simple electric motor.

$$B_o = \mu_o \frac{NI}{l} \quad (1)$$

See Fig. E.

It is common practice to simplify this equation and write it as

$$B_o = \mu_o H \quad (2)$$

in which ***H*** is called the ***magnetic intensity*** and is given by

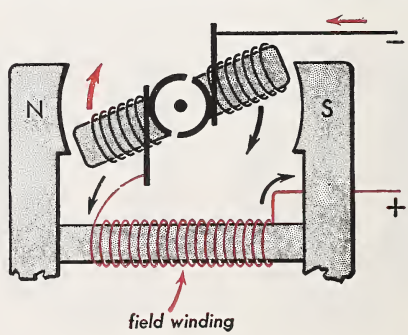
$$H = \frac{NI}{l} \quad (3)$$

When an iron core is inserted into this magnetic field, as shown in Fig. E, the magnetic induction ***B*** increases many fold, and we write

$$B = \mu H \quad (4)$$

where μ is a constant hundreds and even thousands of times larger than μ_o, and is

Fig. G. A field winding makes a more powerful motor.



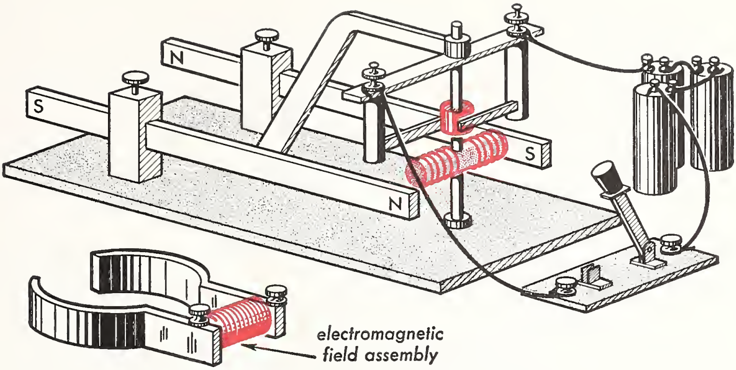


Fig. H. Principal elements of a laboratory type of electric motor.

called the ***permeability.*** The magnetic induction ***B*** beyond but near the coil ends is not greatly different from that at the coil center.

Suppose we now insert such an electromagnet between the poles of a magnet as shown in Fig. F, and arrange sliding contacts that will conduct the required current to the winding and still permit the system to turn. This rotating unit, called the ***armature,*** will experience a very strong resultant torque tending to align it with the magnet's field.

As the armature swings around, to line up the two fields, the current to the armature winding reverses because of the split ring of the commutator. The rotational inertia of the armature then carries it part way around and strong torques again turn it toward alignment.

To further increase the armature torque, the field between the magnet poles is strengthened by sending a current through a coil called the field winding. See Fig. G.

Although electric motors usually have a number of pairs of poles and windings in the armature, and there are many variations in size, shape, and electrical circuits used in their construction, most of the above principles are involved in all of them.

Apparatus. A convenient form of apparatus for this experiment is shown in Fig. H and is called a ***St. Louis motor.*** It consists of two straight bar magnets, an electromagnet attachment, and an armature with sliding contacts and brushes. Additional equipment needed will include three dry cells, a switch, and a rheostat (not shown).

Object. ***To study the principles of electric motors.***

Procedure. ***Part 1.*** Connect the armature brushes to the switch and battery, and with the permanent magnets in place as shown, close the switch. If the armature fails to turn, give it a spin. It should now turn by itself and soon come up to full speed.

Gradually swing the magnet poles away from the armature and record what you observe.

Part 2. Connect the rheostat in series with the armature circuit, and with the field poles close in, close the switch. Note the effect on the speed of the armature as the current is reduced. Record your observations.

Part 3. Reverse the battery connections and note whether the armature rotates in the same direction as before.

Turn the bar magnets end for end, thereby reversing the field direction, and observe whether the armature rotation is reversed or not. Reverse both the armature current and the field magnets and observe the rotational direction.

Part 4. Replace the bar magnets with the electromagnet field assembly. Connect the armature and field winding in series and then to the battery switch. Close the switch and note the direction of rotation.

Part 5. Reverse the battery leads and note the direction of rotation. Reverse the connections to the armature only and note the direction of rotation. Finally reverse the field connections only and note the rotation. Record these observations.

Part 6. Connect the armature and field windings in parallel to the switch. This is called a shunt motor. Close the switch and observe the rotation. Reverse the battery connections and note the direction. Record your observations.

Data. Your data consists of notes on your data sheet made under the headings of Part 1, Part 2, etc. If apparatus is not available for the performance of this experiment, study the principles given in the theory above and see if you can determine the answers to the various steps taken in this experiment.

Results. Answer the following questions in your report.

Part 1. (a) Looking down from above, which way does the armature rotate? (b) What happens as the poles are moved apart?

Part 2. What happens as the armature current increases?

Part 3. (a) What happens when the current is reversed? (b) When the poles are reversed? (c) When both are reversed?

Part 4. In what direction does the armature turn?

Part 5. (a) What is the effect of reversing the battery connections? (b) The armature connections? (c) The field connections?

Part 6. (a) In what direction does the armature rotate? (b) What is the effect of reversing the battery connections?

***Electricity and Magnetism* | Lesson 21**

COULOMB'S LAW

It has been pointed out in Electricity and Magnetism, Lesson 12, that the poles of any magnet are not located at specific points but are distributed about certain areas over the metal surface.

In spite of the uncertainty in the exact location of a magnetic pole, a type of permanent bar magnet has been developed for experimentally determining the laws of force between poles. These special magnets, as shown in Fig. A, consist of thin steel rods, about 20 to 30 cm long, with steel balls at the very ends. When magnetized, the **N** and **S** poles become concentrated on these steel balls.

Note how nearly radially outward the

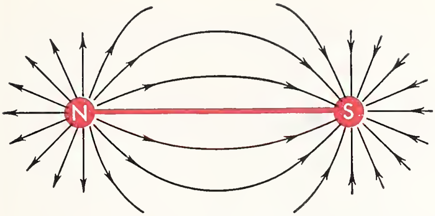


Fig. A. Map of the magnetic field around a special type of permanent magnet.

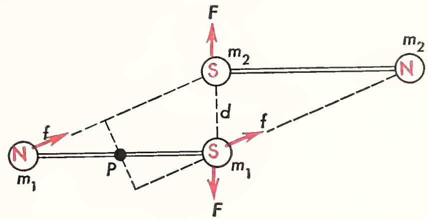


Fig. C. Geometry of the forces and torques involved in the Hibbert balance.

magnetic lines of force are at the **N** pole and how nearly radially inward they are at the **S** pole. The result, in effect, is such as to isolate one pole from the other and at the same time to centralize the field of each pole so that to nearby objects they act as though they were concentrated at the spherical centers.

Theory. A qualitative description of the action between magnetic poles has already been stated in Electricity and Magnetism, Lesson 12, namely, ***like poles repel and unlike poles attract.***

Experimental measurements of a quantitative nature show that ***the force acting between two poles is proportional to the product of the pole strengths and inversely proportional to the square of the distance between them.*** In symbols

$$F = k \frac{mm'}{d^2} \tag{1}$$

where F is the force, m and m' are the pole strengths, and d is the distance between them. This relation is known as Coulomb's law. See Fig. B. In the rationalized mks system of units, F is in newtons, m and m' are

Fig. B. Factors concerned with Coulomb's law for magnetic poles.

in ampere meters, d is in meters, and k is the proportionality constant given by

$$k = 10^{-7} \frac{\text{weber}}{\text{ampere meter}} \tag{2}$$

The magnets to be used in this experiment are of the bar type shown in Fig. A. When two such magnets are arranged in the configuration shown in Fig. C, the two poles nearest each other will exert by far the strongest forces on each other. These forces, represented by F in the diagram, are an ***action*** and ***reaction pair.***

To measure the force F exerted on the lower **S** pole, the lower magnet is initially balanced carefully on a pivot P at its center of mass. Under these conditions the two attractive forces f due to the poles of the upper magnet will cancel out since they exert equal and opposite torques.

If the magnets are long and the distance d relatively small, the force of repulsion between the extreme end poles will be exceedingly small. To a first approximation, this force and the torque it exerts can be neglected.

Apparatus. The apparatus to be used in this experiment is shown in Fig. D and is known as a ***Hibbert balance.*** Two bar magnets, just 20 cm between pole centers, are used, along with a small 10-mg mass in the form of a wire rider R as shown at the lower left.

The upper magnet M_2 is free to be moved up or down, and the rider can be moved

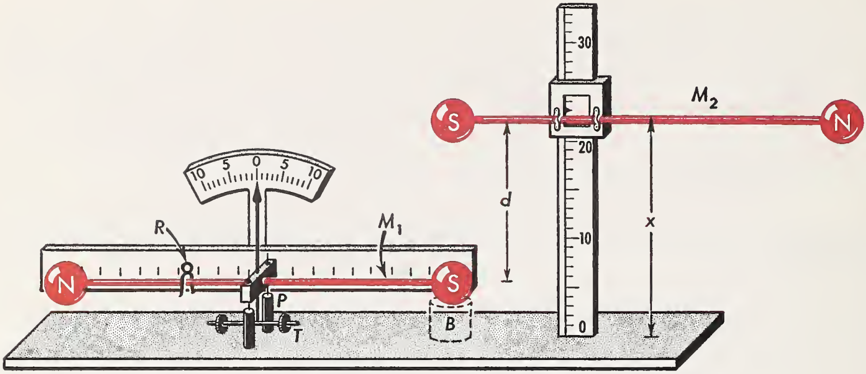


Fig. D. The Hibbert magnetic balance.

along on either side of the lower magnet M_1 to establish balance. By the principle of levers, the force F is determined by the 10-mg rider and its distance from the pivot P.

A small removable gage block B should be provided, and of such a height that when the magnet pole is held down against it, the balance pointer is on zero.

Object. ***To study the inverse square law as it applies to magnetic poles.***

Procedure. To set up the Hibbert balance, select a table free from all iron. Avoid tables containing large steel bolts, gas and water pipes, as well as electrical conduits. Be sure the table surface is level.

With magnet M_1 removed from its pivot, lower magnet M_2 so that its **S** pole rests on the gage block B in exactly the position to be later occupied by the **S** pole of magnet M_1 when in balance. Read the height position on the vertical scale, and record as x_o below Table 1.

Remove magnet M_2 to a distance of at least 10 ft from the balance. Insert M_1 and balance it by adjusting the two thumb screws T. Balance is secured when in the absence of the gage block the magnet is horizontal and the pointer is on zero.

Now place the 10-mg rider R on the magnet bar 1 cm to the left of the pivot P. Bring up M_2 and place it in the vertical support with the two **S** poles lined up vertically as shown.

Slowly lower or raise M_2 until M_1 is exactly in balance again. Read and record the magnet height x. For your data use a table of three columns with headings as shown in Table 1. (*Note:* Since the mass of the rider is 10 mg and the **S** pole of M_1 is 10 cm from the pivot, the rider position, 1 cm to the left of P, is equivalent to the force F of a 1 mg weight at **S**.)

Move the 10-mg rider 2 cm to the left

Table 1. Recorded Data

Trial	F (mg-wt)	x (cm)
1	1	28.7
2	2	21.4
3	3	18.2
4	4	16.4
5	5	15.1
6	6	14.2
7	7	13.5
8	8	12.9
9	9	12.4

$x_o = 5.8$ cm

of P and lower M_2 until M_1 is exactly balanced. Read and record the magnet height x as trial 2.

Repeat this process, moving the rider 1 cm more to the left for each succeeding trial, and record the height x for each position of M_2.

Data. Assume the above experiment has been performed and the data have been recorded as shown in Table 1.

Calculations. It is most convenient to record all calculations by tabulation. For this purpose make two tables of three columns each, with headings as shown in Tables 2 and 3.

Table 2. Calculated Results

d (cm)	d^2 (cm^2)	d^3 (cm^3)
22.9	524	12000

Table 3. Calculated Results

$\frac{1}{d}$ (cm^{-1})	$\frac{1}{d^2}$ (cm^{-2})	$\frac{1}{d^3}$ (cm^{-3})
.0437	.00191	.000083

Calculations for the first trial have already been made and will serve as a guide in making the others.

Results. Plot three separate graphs of your calculations:

(1) Plot F vertically against $1/d$ horizontally.
(2) Plot F vertically against $1/d^2$ horizontally.
(3) Plot F vertically against $1/d^3$ horizontally.

Conclusions. Which of the graphs gives the straightest line? What can you conclude from the results as determined from these three graphs? To what is the slight curvature due in graph number (2)? (*Note:* The plotting of F in mg-wt is justified since each force in dynes is obtained by multiplying the mass in grams by $g = 980$ cm/sec. Hence the values of F listed in Table 1 are very nearly equal to the forces in dynes.)

***Electricity and Magnetism* | Lesson 24**

TRANSFORMERS

The widespread use of transformers, large and small, is ample justification for performing an experiment on this fundamental unit of electrical equipment. The basic principles of the transformer are presented in Electricity and Magnetism, Lesson 22, and involve rapidly changing magnetic fields.

Theory. The transformer, as shown in Fig. A, consists essentially of three important parts: (1) a coil of wire called the ***primary***, (2) another coil of wire called the ***secondary***, and (3) a conductor of magnetic lines of force called the **core** linking both coils.

When a source of alternating current is applied to the two terminals of the primary winding, an alternating emf is produced at the secondary terminals. The increasing and decreasing field B set up in the iron core by the primary a.c. also links through the

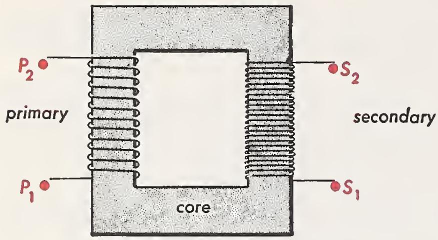


Fig. A. Typical closed-core transformer.

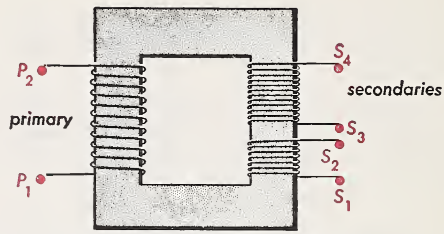


Fig. C. Transformer with two secondaries.

secondary and induces the same difference of potential V_o in every turn of wire. Since the secondary turns are all in series, the over-all voltage delivered is the sum of those for the separate turns. In other words, the secondary voltage V_s should be directly proportional to the number of turns N.

$$\boxed{V_s = V_o N_s} \qquad (1)$$

The relation between primary and secondary voltage and the number of turns in the coils is given by

$$\boxed{\frac{N_s}{N_p} = \frac{V_s}{V_p}} \qquad (2)$$

where N_p and N_s are the number of turns in the primary and secondary, respectively, and V_p and V_s are the corresponding terminal voltages.

If N_s is greater than N_p, we have a so-called ***step-up*** transformer, while if N_s is smaller than N_p, we have a ***step-down*** transformer. The step-up transformer raises the voltage above that applied to the primary, while the step-down transformer reduces it.

A second type of transformer in common use has a tapped secondary. A tapped secondary is one in which different secondary voltages can be obtained by making connections to different numbers of secondary turns as shown in Fig. B. If secondary connections are made to S_o and S_1, a relatively low voltage is obtained. If the upper connection is shifted to S_2, S_3, etc., more and more secondary turns are included, and the secondary voltage is proportionally larger. The effect is similar in many ways to the potential divider.

A third type of transformer of widespread use has two or more independent secondary windings. See Fig. C. Electrically insulated from each other these secondaries produce their own voltage as given by Eqs. 1 and 2.

Apparatus. The principal part of the apparatus used in this experiment consists of a closed core transformer with removable coils, like those shown in Fig. D. A set of

Fig. B. Transformer with a tapped secondary.

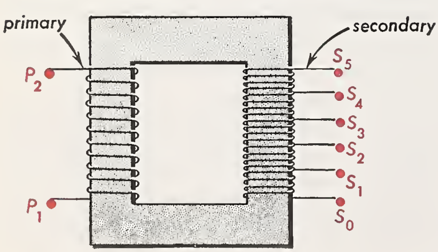
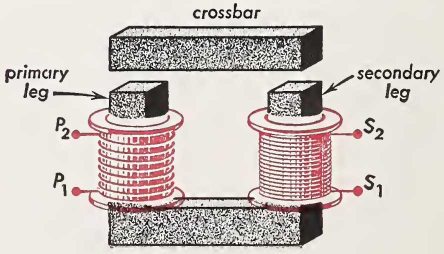


Fig. D. Experimental transformer with changeable coils.



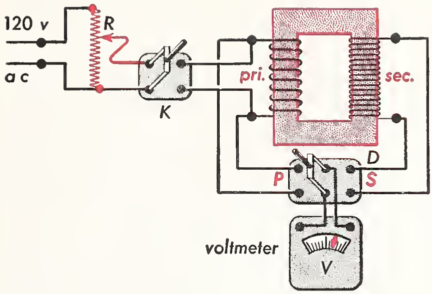


Fig. E. Electrical circuit diagram showing connections for transformer experiment.

several coils wound on the same size tubing but having different numbers of turns are used in pairs for the windings.

Although coils with any desired number of turns may be used, the ones described here have 350, 250, 250, 200, 150, 100, and 50 turns, respectively. In addition to these, a special coil of 100 turns with taps at every twentieth turn, and a tube with two separate windings of 200 turns and 20 turns, respectively, will be used.

The auxiliary equipment needed is shown in Fig. E, and consists of an a.-c. voltmeter reading up to 150 volts, a potential divider of several hundred ohms, a double-pole-single-throw switch, and a double-pole-double-throw switch.

Object. ***To study the principles of the step-up and step-down transformer.***

Procedure. ***Part 1.*** Remove the transformer crossbar. Place the 250-turn coil on the primary leg of the core and the 350-turn coil on the secondary leg. Replace the crossbar and, if a clamp is available, clamp it down tightly.

When all connections are made as shown in Fig. E, close switch **K** and **P**, and adjust the potential divider **P** to give the maximum input voltage to the primary. Read and record this voltage as V_p in a table of four columns as shown in Table 1.

Throw switch **D** to the **S** position and record the secondary voltage reading as V_s. Record the numbers of turns N_p and N_s.

For your second trial replace the secondary coil by one of 250 turns. Be sure the crossbar is secure, and with maximum voltage on the primary, record the secondary voltage V_s. Record N_s and N_p.

For your third and succeeding trials use the other coils in their turn as secondary coils, recording each time V_s, V_p, N_s, and N_p. (*Note:* Do not use a primary winding of less than 100 turns, as an excessive current will be drawn from the 120-volt lighting circuit.)

Part 2. With a 250-turn primary and a 150-turn secondary, carry out the following trials. With the switch **D** to the left, adjust the potential divider to give the primary 100 volts. Throw the switch **D** to the right and find the secondary voltage. Record these readings in Table 1.

With the switch to the left for trial two, adjust the slider to give 80 volts. Throw the switch to the right and read the secondary voltage.

Repeat this procedure, reducing the primary voltage by 20-volt steps, each time recording both voltages V_p and V_s as shown in Table 1.

Part 3. Place the 200-turn coil on the primary leg and the tapped coil on the secondary leg. Set the primary voltage at 100 volts and make the secondary winding connections to tap points S_0 and S_5. See Fig. B.

Read and record your data as shown in Table 1.

Move the upper tap connection from S_5 to S_4 and repeat the voltage measurements. Record these as trial 2.

Repeat these steps for each tap on the secondary winding and record.

Part 4. Replace the tapped secondary by the tube containing two separate coils. Connect

the voltmeter leads to each coil in turn, and with the primary at 110 volts, determine the secondary voltage for each secondary coil. Record these readings as shown in Table 1.

Data. We will assume the above steps have been carried out and the data recorded as shown in Table 1.

Table 1. Recorded Data

N_p (turns)	N_s (turns)	V_p (volts)	V_s (volts)
Part 1			
250	350	118	150
250	250	118	107
250	200	118	86
250	150	118	64
250	100	118	43
250	50	118	22
Part 2			
250	150	100	55
250	150	80	43
250	150	60	32
250	150	40	22
250	150	20	11
Part 3			
200	100	100	46
200	80	100	37
200	60	100	28
200	40	100	18
200	20	100	9
Part 4			
200	200	110	101
200	20	110	10

Calculations. Make a table of two columns with headings as shown in Table 2. The two ratios shown should be computed for all trials recorded in Table 1. The first two trials are already calculated and will serve as a guide for all the others.

By Eq. (2) we should expect each pair of values to be the same. Transformers, however, are not 100% efficient. A small amount of energy is dissipated as heat both in the coils and in the soft iron of the core. The core of most transformers is laminated, i.e., made up of thin layers, for the purpose of reducing losses due to eddy curents induced in the core by the changing field. As a rule, transformers are over 90% efficient.

Table 2. Calculated Results

$\frac{N_s}{N_p}$	$\frac{V_s}{V_p}$
Part 1	
1.40	1.27
1.00	.91

Results. Plot a graph of your recorded data in Part 1. Plot V_s vertically with the scale labeled 0, 25, 50, 75, 100, 125, and 150 volts, and N_s horizontally with the scale labeled 0, 100, 200, 300, and 400 turns. Use a ruler and draw as straight a line as you can through the plotted points. Using this graph, read off the value of V_s if a secondary of 300 turns had been used in Part 1. From this V_s and N_s, and Eq. (1), calculate the voltage per turn V_o.

ATOMIC PHYSICS

ELECTRONIC CHARGE TO MASS RATIO

The purpose of this experiment is to determine by measurement and calculation the ratio of the electronic charge **e** to the electronic mass **m**. This is known as the ***"e over m experiment,"*** and you should find it most interesting.

Theory. When any substance is heated to incandescence in a vacuum, it not only gives off visible light radiation but it also emits electrons as well. Such action is illustrated in Fig. A, and is called ***thermionic emission.***

The thermal emission of electrons by a hot tungsten filament ***F***, heated to incandescence by the current from a battery, is analogous to the steam boiling off from a tea kettle. The higher the current, the higher is the surface temperature of the metal and the greater are the number of electrons emitted.

The surface temperature required for the copious emission of electrons is greater for some materials than for others. Low temperature emitters are often used in electronic devices, heated to their proper temperature by an indirect heating element as shown in Fig. B.

This particular device, called an ***electron gun,*** is for the purpose of producing a strong but narrow beam of electrons. A battery of a few volts, applied to a tungsten wire filament ***F***, indirectly heats the electron-emitting surface ***K*** called the cathode.

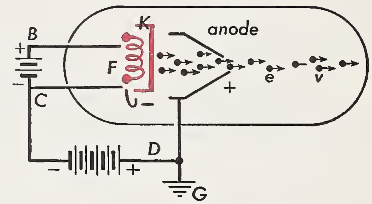


Fig. B. Diagram of an electron gun.

With a battery of several hundred volts ***V***, these electrons are accelerated toward the positively charged, cone-shaped anode. By grounding the plus side of the battery the anode is brought to the potential of the surroundings, and the electrons, emerging as a beam, travel with constant speed.

We have seen in Electricity and Magnetism, Lesson 16, that if the difference of potential between two terminals is ***V***, the work done on each charge **e** in going from one to the other is given by ***Ve***. Since this work is converted into kinetic energy by giving electrons a velocity **v**, we can write

$$\boxed{Ve = \tfrac{1}{2}mv^2} \qquad (1)$$

This is one of the basic equations in atomic physics.

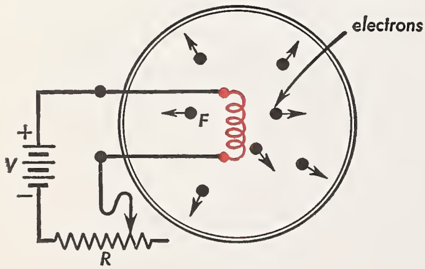
Solving for **v**, we obtain

$$v = \sqrt{\frac{2Ve}{m}} \qquad (2)$$

If ***V*** is in volts, **e** is in coulombs, and ***m*** is in kilograms, **v** is in meters per second. For electrons

$$e = 1.6019 \times 10^{-19} \text{ coulomb} \qquad (3)$$
$$m = 9.1072 \times 10^{-31} \text{ kg} \qquad (4)$$

Fig. A. Thermionic emission.



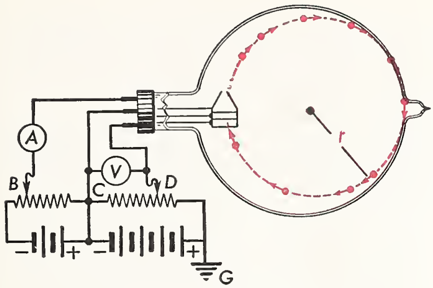


Fig. C. Circuit diagram for e/m experiment.

Apparatus. The apparatus used in this experiment consists, as shown in Fig. C, of a highly evacuated glass bulb containing an electron gun as just described. With the entire tube located in the uniform magnetic field of two current-carrying coils, the emergent beam is bent into a circular path as shown.

The battery circuit is for the purpose of supplying current to heat the cathode of the electron gun, as well as the voltage needed to accelerate the liberated electrons.

Since the electrons travel through a magnetic field, their circular path is determined by Eq. (2) of Atomic Physics, Lesson 3. This equation gives

$$v = \frac{Ber}{m} \tag{5}$$

Since the left-hand sides of Eqs. (2) and (5) are equal to each other, we can set the right-hand sides equal:

$$\frac{Ber}{m} = \sqrt{\frac{2Ve}{m}}$$

Squaring both sides of this equation, we obtain

$$\frac{B^2e^2r^2}{m^2} = \frac{2Ve}{m}$$

Canceling out like quantities, we can solve for e/m, and obtain,

$$\boxed{\frac{e}{m} = \frac{2V}{B^2r^2}} \tag{6}$$

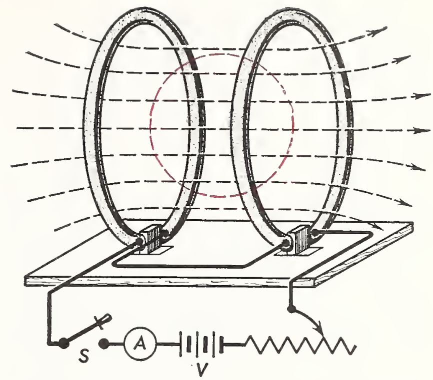


Fig. D. Helmholtz coils for producing a uniform magnetic field.

All the quantities on the right are to be measured. The accelerating voltage V applied to the electrons is measured with a voltmeter, the radius r of the circular path is measured with a meter stick, and the magnetic induction B is determined from the known dimensions of, and the current flowing through, Helmholtz coils. As shown in Fig. D, Helmholtz coils consist of two identical coils placed side by side at a distance apart equal to their radius R.

Such an arrangement produces a relatively uniform field over a considerable volume of space, and the magnetic induction is given by

$$\boxed{B = 9.0 \times 10^{-7} \frac{NI}{R} \frac{\text{weber}}{\text{meter}^2}}$$

where N is the number of turns per coil, R is the coil radius in meters, and I is the current in amperes. The number of turns of wire can be counted, the radius can be measured with a meter stick, and the current can be read from an ammeter as shown in Fig. D.

Object. *To determine the electronic charge to electronic mass ratio.*

Procedure. Since this kind of equipment is delicate and easy to damage, follow the

instructions usually found attached to the apparatus by the manufacturer.

Turn on the heater current and bring the current up to the specified value. After about 60 sec, turn on the accelerating potential ***V*** and bring it up to 155 volts.

Turn out the room lights, and the electron beam should appear coming straight up out of the opening of the electron gun. The fluorescence of the small amount of hydrogen gas, or mercury vapor, in the evacuated bulb should make the beam visible. Make a table of three columns and record this voltage in the first column as shown in Table 1.

Now apply the field current to the Helmholz coils. The electron beam will now bend in the arc of a circle. Adjust the coil current until the beam just misses the glass walls of the tube opposite the gun as shown in Fig. C. Read and record the current ***I***.

As a second trial, increase the accelerating voltage to 175 volts. Increase the field current until the beam just misses the opposite glass wall. Read and record the voltage ***V*** and current ***I*** as shown in Table 1.

Increase the accelerating voltage another 20 volts and repeat the procedure as before.

Measure the number of coil turns and the coil radius, and record them below your table as shown in the example (Table 1).

To measure the diameter of the circular beam of electrons, the beam can be turned off and the room lights left on. Set up a meter stick in a clamp stand and sight into the tube using a right triangle of the type used in drafting. Record the radius ***r***.

Data. Assume that the above steps have been properly carried out and the data recorded as shown in Table 1.

Table 1. Recorded Data

Trial	V (volts)	I (amps)
1	155	.94
2	175	1.01
3	195	1.06

radius of coils $R = .18$ m
wire turns per coil $N = 123$
radius of electron beam $r = .072$ m

Calculations. Make a table of five columns with headings as shown in Table 2. Make the necessary calculations to find the ratio **e/m** for all three trials.

Compute your average **e/m** and compare it with the most probable value known to date:

$$\frac{e}{m} = 1.759 \times 10^{11} \frac{\text{coulomb}}{\text{kg}}$$

Table 2. Calculated Results

NI $\left(\frac{\text{amp}}{\text{turns}}\right)$	B $\left(\frac{\text{webers}}{\text{meter}^2}\right)$	B^2r^2 $\left(\frac{\text{webers}^2}{\text{meters}^2}\right)$	$2V$ (volts)	e/m $\left(\frac{\text{coulomb}}{\text{kg}}\right)$

Atomic Physics | Lesson 6

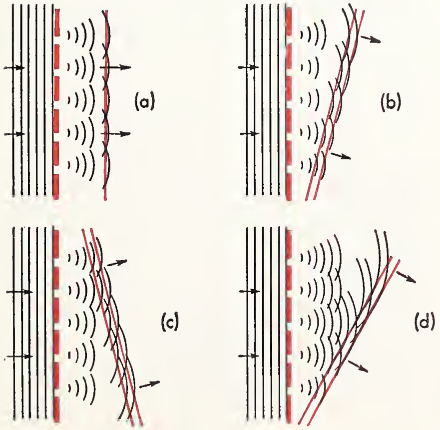
WAVE LENGTHS OF SPECTRUM LINES

The wave lengths of visible light emitted by different light sources are so extremely short that approximately one thousand waves are no longer than the thickness of a sheet of paper. As short as they are, light of various wave lengths from any given source can be measured with very high precision.

Theory. The most common methods used in the research laboratory for measuring the wave length of light employ a diffraction grating. If the instrument is designed to photograph the spectrum, it is called a ***spectrograph;*** if it is designed to look at the spectrum, it is called a ***spectroscope.***

We have seen in Light, Lesson 16, that a diffraction grating is composed of thousands of fine parallel and equally spaced lines ruled on a smooth surface. If the surface is that of a mirrorlike reflector it is a ***reflection grating,*** and if the surface is that of a transparent medium like glass or plastic it is a ***transmission grating.***

Fig. A. Diagrams showing the wave fronts forming the various spectrum orders observed with a diffraction grating.

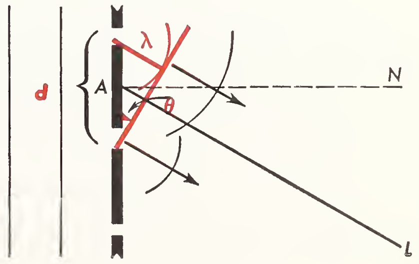


While a grating may contain several thousand lines per centimeter, the theory of its action on light can be derived from the consideration of but a few of the lines. Fig. A represents a cross-section diagram of a small section of a transmission grating, the lines being seen end on.

Parallel light waves coming from the left are partly absorbed, partly reflected by the rulings, and partly transmitted. Emerging from the openings as identical wavelets, a number of wave fronts of light are built up as shown by the parallel lines. One set of light waves travel straight on, while others travel off at angles.

The new wave fronts in diagram (b) or (c) constitute what is called the ***first-order spectrum,*** while those in diagram (d) form what is called the ***second-order spectrum.*** To find a relation between measurable quantities and the wave length of light consider the wavelets emerging from two adjacent slits to form the first-order spectrum as shown in Fig. B. Note the right triangle

Fig. B. Diagram from which the grating formula is derived.



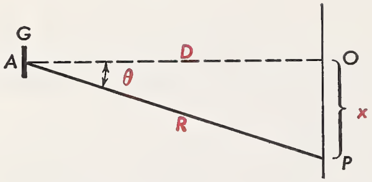


Fig. C. Diagram for the diffraction grating measurements.

formed by the grating spacing **d** as the hypotenuse, and the wave length λ as the side opposite the angle θ. From this triangle we can write

$$\frac{\lambda}{d} = \sin\theta \qquad (1)$$

Transpose **d** to the other side and we obtain the basic equation for diffraction gratings

$$\lambda = d\sin\theta \qquad (2)$$

The wave front normal ***AL*** and grating normal ***AN*** also form the angle θ and, at a screen some distance away, form a similar right triangle ***AOP***. See Fig. C. For this triangle

$$\frac{x}{R} = \sin\theta \qquad (3)$$

Combining Eqs. (1) and (3), or from the corresponding sides of similar triangles, we can write

$$\frac{\lambda}{d} = \frac{x}{R} \qquad (4)$$

from which we obtain

$$\boxed{\lambda = \frac{xd}{R}} \qquad (5)$$

A diagram similar to Fig. B, drawn for the second-order spectrum as shown in Fig. A(d), shows that the side opposite the angle θ has a length of 2λ. From similar right triangles in this case,

$$\frac{2\lambda}{d} = \frac{x}{R'} \qquad (6)$$

from which we obtain

$$\boxed{\lambda = \frac{xd}{2R'}} \qquad (7)$$

Because the wave lengths of light are so very small, the physicist has adopted a smaller unit of length than the centimeter or millimeter. This unit is called the ***angstrom*** after the Swedish scientist by that name. In 1868, Angstrom published a map of the visible spectrum of the sun, and on this map he labeled the wave lengths in ten-millionths of a millimeter. Since that time, light waves have been specified in these units.

In one centimeter there are 100,000,000 angstroms.

$$1\text{ cm} = 10^8\text{ A} \qquad (8)$$

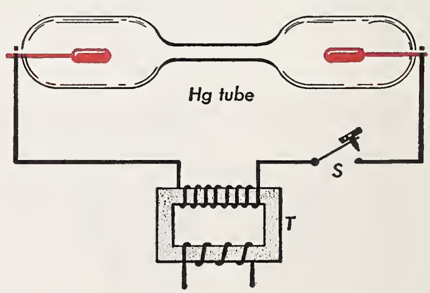
In light the velocity **c** in a vacuum is given by

$$c = \nu\lambda \qquad (9)$$

where ν is the vibration frequency and λ is the wave length. From this we see that the longer the wave length, the lower is the frequency; and the shorter the wave length, the higher is the frequency. It is common practice among physicists to designate the wave length of light waves by the Greek letter λ (lambda) and the frequency by the Greek letter ν (nu).

Apparatus. The source of light used in this experiment is a mercury vapor discharge tube of the form shown in Fig. D. A small

Fig. D. Mercury vapor discharge tube.



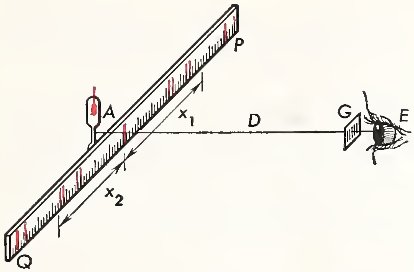


Fig. E. Arrangement for the diffraction grating as used in this experiment.

step-up transformer connected to a regular 110-volt a.-c. source supplies high voltage to the electrodes in the ends of the tube. When the lamp is turned on, the discharge is brightest in the central capillary section, and the light emitted is characteristic of the mercury atoms inside.

The spectroscope arrangement to be used employs a small transmission grating, as shown in Fig. E. Light entering the slit at ***A*** passes through the grating ***G*** to the eye ***E***. Looking into the grating, the eye sees the direct image of the slit at ***A***, as well as a number of colored images of the slit along the meter stick.

Object. ***To determine the wave lengths of light emitted by certain atoms.***

Procedure. Make a table of four columns on your data sheet and label them as shown in Table 1.

Mount the diffraction grating about 60 cm from the slit, being sure the line of sight ***AG*** is perpendicular to ***PQ***. Turn on the light source and line it up with the slit.

Looking through the diffraction grating, locate the exact position of the violet spectrum line on each side of the slit. Find the two distances x_1 and x_2, determine the average, and record the result in column 3.

Now locate the blue lines nearest the slit but on opposite sides, and find their distances x_1 and x_2. Take the average and record the result as x in column 3.

Repeat this procedure for the green and yellow lines, and record them as indicated.

If any of the lines can be seen farther out, they constitute the second order and may be recorded in the same way.

(If other sources, like hydrogen or helium discharge tubes, or a sodium flame, are available, set each one in front of the slit in turn and make similar measurements.)

Measure and record the distance ***D*** from slit to grating.

Examine the grating for markings and record either the number of ruled lines per centimeter or the grating spacing ***d***. (Replica gratings are usually labeled with one or the other of these measurements.)

Data. Assume the above steps have been properly carried out and the data have been recorded as shown in Table 1.

Table 1. Recorded Data

Element	Color (order)	x (cm)	D (cm)
mercury	violet (1)	15.55	61.8
mercury	blue (1)	16.80	61.8
mercury	green (1)	21.50	61.8
mercury	yellow (1)	22.90	61.8
mercury	violet (2)	34.50	61.8
mercury	blue (2)	38.10	61.8

Grating has 6025 lines per cm.
This gives $d = .0001660$ cm.

Calculations. Make a table of five columns with headings as shown in Table 2. Fill in the columns for each spectrum line observed by using Eq. (5) or (7). The first row of values for the violet line is already completed and will serve as a guide for the

Table 2. Calculated Results

R (cm)	$\sin\theta$	λ (cm)	λ (calc.) (A)	λ (acc.) (A)
63.72	.2440	.00004050	4050	4047

others. Carry out all calculations to four significant figures. Use Eq. (3) for computing column 2.

The accepted wave lengths for the mercury lines are 4047 A, 4359 A, 5461 A, and 5770 A, respectively.

Plot a graph of sin θ against calculated λ for the first-order lines only. Use ten squares vertically for sin θ, and label them .160, .180, .200, . . . , .360. Use ten squares horizontally for λ, and label alternate lines 4000, 4400, 4800, . . . , 6000 A.

Conclusions. What conclusions can you draw from the graph? Would the graph line pass through the origin if drawn? Do you think a diffraction grating instrument is capable of high precision?

***Atomic Physics* | Lesson 9**

RADIOACTIVITY MEASUREMENTS

Radioactivity may be defined as the spontaneous disintegration of atomic nuclei. We have seen in Atomic Physics, Lesson 8, that three kinds of rays are ejected from radioactive elements and that these rays, called alpha, beta, and gamma rays, have different ionizing and penetrating powers.

When a strong radioactive source, like radium, is brought close to a charged electroscope, or an electrometer, rays passing through the housing ionize the air molecules inside. Some of these ions are attracted to the electroscope and neutralize its charge.

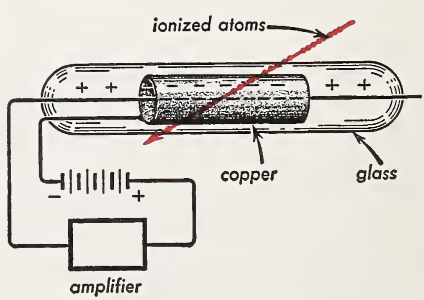
Theory. A most effective detector of radioactivity, known as a ***Geiger counter,*** is to be used in this laboratory experiment. The principal element of this device, known as a ***Geiger-Mueller tube,*** is one of the simplest devices ever designed. It consists, as shown in Fig. A, of an open-ended cylindrical conductor, from 1 cm to 100 cm long, fitted inside of a sealed thin-walled glass tube, and with a fine tungsten wire stretched along the axis.

After the tube has been evacuated, and then partially filled with some gas, like air, a potential of several hundred volts is applied, the positive to the center wire and the negative to the cylinder.

When a single high-speed particle from a radioactive source goes through the Geiger-Mueller tube, ions are created along its path by the freeing of electrons from the gas molecules.

These freed electrons are attracted to the positively charged wire and move toward it, acquiring within a short distance of the wire a high velocity of their own. Because of this velocity they too can ionize molecules, thus freeing more electrons. This multiplication of electrons repeats itself in rapid succession,

Fig. A. Diagram of a Geiger-Mueller tube.



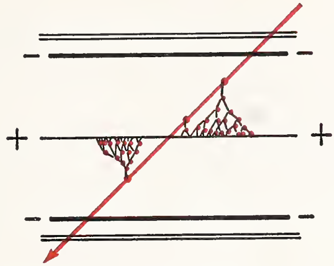


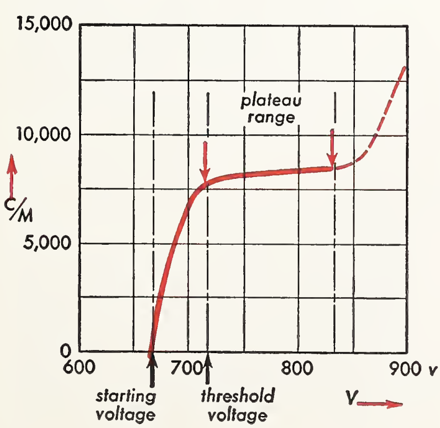
Fig. B. Electron avalanches developed in a Geiger-Mueller tube.

producing within a very short interval of time an avalanche of electrons surging toward the central wire. See Fig. B.

The sudden arrival of charge at the wire gives rise to the flow of a small current impulse to an electrical circuit. When this current has been intensified by an amplifier, it may be made to activate an electric switch, a radio loud-speaker, or any kind of electrical device.

Quite frequently the impulses from a Geiger-Mueller tube are made to operate a small counting device, or a meter that indicates the number of particles passing through it per minute. The latter type of attachment makes the instrument a Geiger counter with a counting-rate meter.

Fig. C. Characteristic curve for a Geiger-Mueller tube.



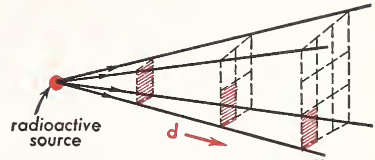


Fig. D. Illustration of the inverse-square law for radioactivity.

When a radioactive source is brought close to a Geiger counter and the counting rate determined for different applied voltages, one obtains a curve like that shown in Fig. C. As the voltage is slowly increased, no counts are observed until a certain ***starting voltage*** is reached.

Once the starting voltage is reached, the counting rate increases rapidly and then levels off to form a flattened part of the curve called the ***plateau.*** When operating with a voltage near the center of this region, any increase or decrease of 50 volts or so will not appreciably alter the instrument's counting rate.

If the applied voltage goes too high, as shown by the dotted part of the graph, the tube becomes unstable and a glow discharge will develop, causing damage to the tube.

As a radioactive source is brought closer and closer to a Geiger counter, the counting rate increases because more rays pass through it. Because of the straight line path of the rays, the ***inverse-square law,*** found to hold for sound waves and for light, should hold for α, β, and γ rays. See Fig. D. Ionization by, and absorption of, rays along their paths through the air will cause departures from this law. The α particles travel but a few centimeters before all are stopped, while most of the β and γ rays will traverse 100 cm or more.

Apparatus. The apparatus to be used in this experiment is a common form of Geiger counter as shown in Fig. E. It consists of a G-M counter tube about 10 cm long connected to a box containing vacuum

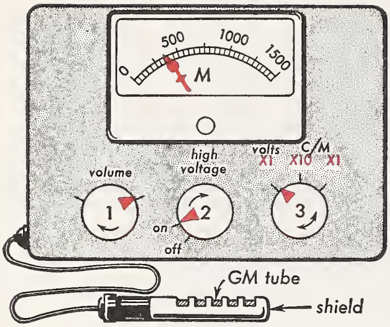


Fig. E. Geiger counter instrument complete with G-M tube and counting-rate meter.

tube circuits, a small loud-speaker, and a counting-rate meter ***M***.

Dial (1) operates the speaker and permits the individual ray pulses to be heard. Dial (2) turns on the vacuum tubes as in any radio or TV receiver, and turning it clockwise increases the voltage supplied to the G-M tube. Dial (3) has three position points to which it can be turned. The position marked "VOLTS" connects the meter ***M*** so it shows the voltage on the G-M tube. When in the X 1 position, under C/M, the meter ***M*** directly reads counts per minute, and in the X 10 position the meter reading should be multiplied by 10.

A small capsule containing a source of radium, or a watch with a radium painted dial, may be used as a source of β and γ rays.

Object. ***To measure the radioactivity of a radioactive element by means of a Geiger counter.***

Procedure. Be sure dial 2 is in the "OFF" position before plugging the instrument cord into the wall socket. Turn dial 3 to the "VOLTS" position and dial 1 clockwise as far as possible (maximum volume). Dial 2 should now be turned clockwise just enough to turn the instrument on. As the tubes warm up, the meter will rise to some steady value.

Part 1. Place the radioactive source near the counter and slowly turn dial 2 clockwise. Note the minimum voltage at which counts are first heard. Increase the voltage 50 volts above this threshold.

Turn dial 3 to the X 10 position and move the source until the meter reads about 600. This gives a count rate of about 6,000 counts per minute. Do not move the G-M tube or the source as the following steps are carried out.

Turn dial 3 to the "VOLTS" position, and with dial 2 locate the starting voltage reading. Record this voltage in a table of three columns as shown in Table 1.

Raise the voltage 25 volts, and turning dial 3 to the X 10 position, record the counting rate.

Continue to raise the voltage by 25-volt steps and record the corresponding counts per minute (*abbr.* C/M). The voltage should not be raised over 150 volts beyond the ***threshold.***

Plot a graph with C/M on the vertical scale and volts on the horizontal scale. If the plateau region slopes upward by more than a 5% increase in C/M for a 100-volt increase in voltage, the G-M tube should be replaced by a new one and the measurements repeated.

Part 2. Adjust the counter voltage to the center of the plateau. With the radioactive source ten feet from the G-M counter, turn dial 3 to the X 1 position. Slowly bring up the source until the counting rate meter shows about 100 C/M.

With the zero end of the meter stick at the G-M counter, move the source to the nearest 10-cm mark and record the C/M as trial 1. See Table 2.

Move the source 10 cm closer to the G-M counter and record the C/M for trial 2.

Repeat these measurements, moving the source 10 cm closer for each trial. When the C/M are too high for the X 1 position, turn dial 3 to the X 10 position and con-

tinue until you obtain readings of the order of 10,000 C/M. At closest range, 5 cm changes in distance are advisable.

When turning off the instrument, dial 3 should be turned to the "VOLTS" position and dial 1 fully clockwise. This will greatly reduce the possibility of damage when the instrument is turned on again.

Table 1. Recorded Data, Part 1

Trial	V (volts)	Activity (C/M)
1	675	—
2	700	4800
3	725	5300
4	750	5350
5	775	5400
6	800	5450
7	825	5500

Table 2. Recorded Data, Part 2

Trial	Distance (cm)	Activity (C/M)
1	80	150
2	70	200
3	60	280
4	50	400
5	40	600
6	30	1100
7	20	2500
8	15	4300
9	10	8800

Data. Assuming that the above steps have been carried out, your recorded data will have the appearance of that shown in Tables 1 and 2.

Calculations. Make a table of three columns with headings as shown in Table 3. Fill in the columns, using the data recorded in Part 2. The results for the first trial are already completed and will serve as a guide for the others.

Table 3. Calculated Results

Trial	Activity (C/M)	$1/d^2$ (cm^{-2})
1	150	.000156

Results. Plot a "PLATEAU" curve from your data in Table 1. The activity in C/M should be plotted vertically, and the applied voltage ***V*** horizontally.

Plot a second graph from your data recorded in Table 2. The activity in C/M should be plotted vertically against distance ***d*** in centimeters plotted horizontally.

Plot a third graph from your tabulated results in Table 3. The activity in C/M should be plotted vertically against $1/d^2$ horizontally. This curve will give a visual test of the inverse square law.

Conclusions. Briefly explain why your third graph is slightly curved. Remember the β and γ rays must travel through the air.

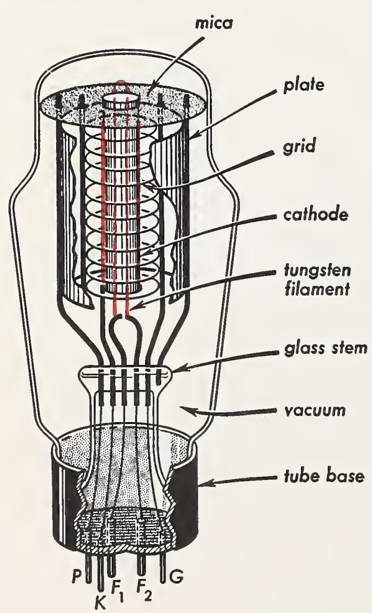
ELECTRONICS

CHARACTERISTICS OF VACUUM TUBES

Every radio enthusiast today knows there are hundreds of different kinds of radio tubes. Some contain two filaments and two plates, while others contain as many as three or four separate grids. Although a treatment of such complex tubes is out of place here, the fundamental principles of all of them are little different from DeForest's audion. One important difference, however, is illustrated in Fig. A, and that is the employment in some tubes of a cathode in place of a filament as a source of thermal electrons.

A fine tungsten-wire filament is threaded through two small holes running lengthwise through a porcelainlike insulating rod. Fitting snugly around this rod is the cathode, a metal cylinder coated on the outside with a thin layer of thorium, strontium, or cesium oxide. These particular oxides are copious emitters of electrons when heated to a dull red heat. Insulated from the cathode, the filament as a source of heat can be, and generally is, connected directly to an appropriate transformer winding.

Fig. A. Modern radio tube with a cesium-coated cathode as a source of thermal electrons. The filament serves only to heat the cathode.



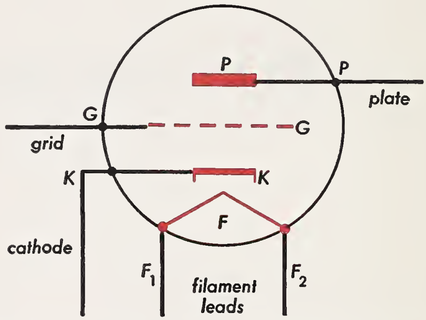
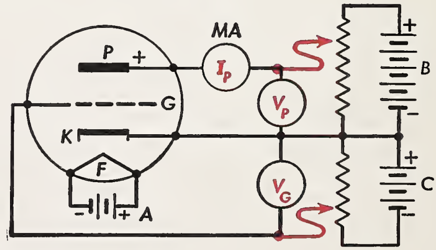


Fig. B. Schematic diagram of a cathode type of radio tube.

A schematic diagram of the cathode type of tube containing one plate and one grid is given in Fig. B.

Theory. A circuit diagram showing the electrical connections and instruments

Fig. C. Circuit diagram for determining the characteristics of a triode vacuum tube.



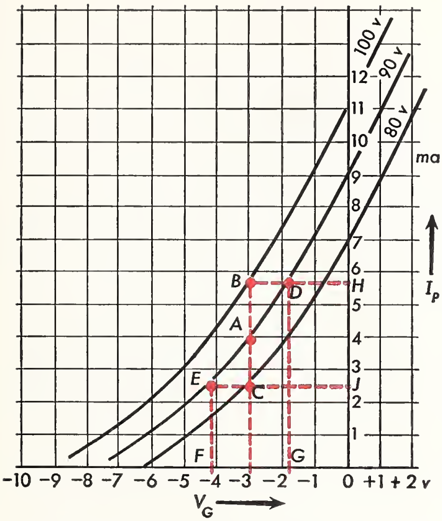


Fig. D. Characteristic curves for a triode vacuum tube.

needed to measure the ***grid-voltage vs plate-current*** curve for vacuum tubes in general is given in Fig. C. A variable voltage is applied to the plate ***P*** by a potential divider and a **B** battery, and a variable voltage is applied to the grid **G** by another potential divider and a **C** battery. The various applied voltages are read from voltmeters V_P and V_G, respectively, and the corresponding plate current is read from a milliammeter ***MA***.

Three characteristic curves taken with the above circuit connections are reproduced in Fig. D, one for each of three plate voltages, 80, 90, and 100 volts respectively.

The foot of each curve, near −6 to −9 volts, indicates that with these negative potentials on the grid very few electrons are able to reach the plate. As the grid is made less and less negative, more and more electrons get through, thereby increasing the current to the plate. The higher the positive potential on the plate, the higher is the plate current, and the more negative must be the grid to stop the electrons.

The dotted lines near the center of the curves illustrate the meaning of what is called the voltage amplification factor μ of the tube. ***The change in plate voltage giving rise to a change in plate current divided by the change in grid voltage that will give rise to the same change in plate current is called the voltage amplification factor μ.***

To illustrate the meaning of μ, consider the point ***A*** on the 90-volt center curve where the grid voltage is −3 volts. Where the vertical line through ***A*** intersects the upper and lower curves at ***B*** and **C**, horizontal dotted lines are drawn as shown. Where these lines intersect the 90-volt curve at ***D*** and ***E***, vertical dotted lines are drawn downward, intersecting the baseline at ***F*** and **G**.

It can now be seen from the graph that if we maintain the plate voltage at +90 volts and then change the grid voltage from ***F*** to **G**—a change of about 2.4 volts—the plate current will rise from ***J*** to ***H***. To change the plate current this same amount by keeping the grid voltage at −3 volts, the plate voltage must be increased from 80 volts at **C** to 100 volts at ***B***, or 20 volts. Hence the voltage amplification factor is

$$\mu = \frac{20 \text{ volts}}{2.4} = 8.3$$

Apparatus. The circuit connections for this experiment are shown in Fig. C, and consist of two voltmeters, a milliammeter, two rheostats, three batteries, and a triode vacuum tube. Any one of a large number of three-element vacuum tubes may be used, and the batteries should be so chosen as to enable the proper voltages to be applied to the filament, grid, and plate.

Object. ***To determine the grid-voltage and plate-current characteristics of a three-element vacuum tube.***

Procedure. Make a table of three columns with headings as shown in Table 1.

After making all connections as shown in Fig. C, turn on the tube filament. After a warm-up period of about three minutes, set the plate voltage at +95 volts and the grid voltage at zero. Read the three meters and record the plate voltage V_P, the grid voltage V_G, and the plate current I_P, as shown in the first row.

Keep the plate voltage at +95 volts and set the grid voltage at −1 volt. Read the three meters again and record.

Repeat this procedure, changing the grid voltage by 1 volt at a time and keeping the plate voltage constant at +95 volts, until the plate current I_P drops below 1 ma.

To obtain a second set of readings, lower the plate voltage V_P to +85 volts and the grid voltage V_G to zero. Read and record the three meter readings.

Repeat the above procedure, changing the grid voltage by 1-volt steps and keeping the plate voltage constant at +85 volts, until the plate current I_P drops below 1 ma.

For a third set of readings, lower the plate voltage V_P to +75 volts and the grid voltage V_G to zero, and repeat the above meter readings with 1-volt changes in V_G. (*Note:* Changing the grid voltage may effect the plate voltage slightly, making it necessary to readjust the plate potentiometer when the grid potentiometer is moved.)

Data. Assuming the above steps have been properly carried out, the recorded meter readings will appear as shown in Table 1.

Table 1. Recorded Data

V_P (volts)	V_G (volts)	I_P (volts)
+95	0	9.7
	−1	8.0
	−2	6.5
	−3	5.3
	−4	4.2
	−5	3.2
	−6	2.4
	−7	1.7
	−8	1.2
	−9	0.8
+85	0	6.6
	−1	7.1
	−2	5.3
	−3	4.1
	−4	3.1
	−5	2.2
	−6	1.5
	−7	1.0
	−8	0.5
+75	0	6.7
	−1	5.3
	−2	4.1
	−3	3.0
	−4	2.2
	−5	1.5
	−6	0.9

Calculations. Plot the characteristic curves from your data recorded in Table 1.

Draw horizontal and vertical dotted lines on the graph and determine the voltage amplification factor at $V_G = -2$ volts.

Electronics | Lesson 6

ELECTROMAGNETIC WAVES

This laboratory lesson is concerned with high-frequency radio waves. The basic relation involved is the well-known wave equation

$$c = \nu\lambda \tag{1}$$

where ν is the frequency, λ the wave length, and c the speed of the waves. In a vacuum, c is the same for all electromagnetic waves and is equal to the speed of light

$$c = 3 \times 10^8 \frac{\text{m}}{\text{sec}} \tag{2}$$

A chart of the electromagnetic spectrum extending from the shortest known waves, the γ rays, to the longest known waves of radio is given in Fig. A. The long wavelength end of this chart is seen to be divided into equally spaced bands with the designations shown in Table 1.

The SHF and EHF bands are frequently referred to as ***microwaves.***

Theory. Most generators of radio waves involve the use of vacuum tubes and oscillating circuits. We will not be concerned in this lesson with the tubes and circuits, but rather with the source antennas; the wave lengths; frequencies, behavior, and nature of the waves emitted; and the receiving antennas.

Fig. B shows an Hertzian dipole ***T*** emitting electromagnetic waves, which, after traveling some distance, are received by a similar dipole. These waves, vibrating with the electric intensity ***E*** in a plane of the dipole, are polarized. As they pass the receiver, the electrons in the metal rods of the dipole experience periodic forces which by the principle of resonance give rise to an alternating emf of the same frequency as the source.

When such a dipole is oscillating, a voltage node exists at the center and voltage antinodes at the extreme ends, so that the natural resonant frequency is such that each arm of the dipole is $\frac{1}{4}\lambda$. Hence a dipole made up of two 1-m arms will respond to 4-m waves, which by Eqs. (1) and (2) correspond to a frequency of

$$\nu = \frac{3 \times 10^8}{4} = 75\ \text{Mc/sec}$$

If a straight conductor is stretched between transmitter and receiver, microwaves

Table 1. Radio Wave Bands

Band Designation		ν	λ
VLF	very low frequency	3 Kc	100 Km
LF	low frequency	30 Kc	10 Km
MF	medium frequency	300 Kc	1 Km
HF	high frequency	3,000 Kc	100 m
VHF	very high frequency	30 Mc	10 m
UHF	ultra high frequency	300 Mc	1 m
SHF	super high frequency	3,000 Mc	10 cm
EHF	extremely high frequency	30,000 Mc	1 cm
		300,000 Mc	.1 cm

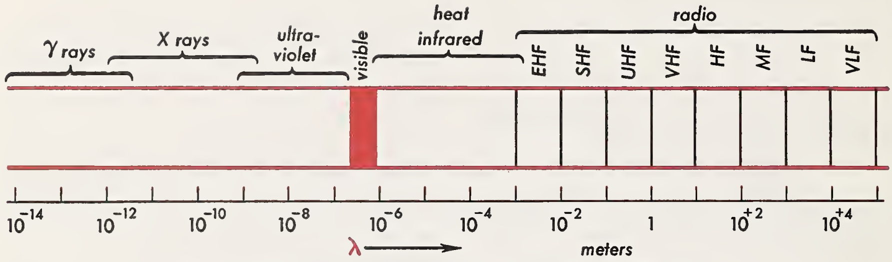


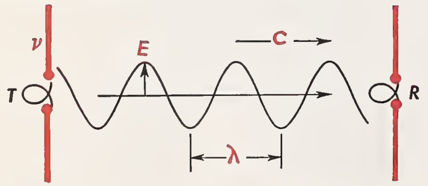
Fig. A. Electromagnetic spectrum showing wave lengths of radio bands.

tend to follow the conductor and at the same time maintain very nearly their speed in a vacuum. If, however, the wire is wound into a long helical coil as shown in Fig. C, the conductor still acts as a guide but the speed of the waves is considerably attenuated. Furthermore, on reaching the end they behave like transverse waves on a rope and reflect back and set up standing waves. Nodes and antinodes on such a wave guide are readily detected by means of a small tungsten filament lamp. The alternating emf developed in the lamp filament when located at a voltage antinode causes it to light up.

Object. ***To study the properties of electromagnetic waves in the VHF and microwave region of the spectrum.***

Apparatus and Procedure. Two transmitters of high-frequency electromagnetic waves will be used in this experiment. Both are commercial products found in many physics laboratories, and each will be described as measurements are made.

Fig. B. Electromagnetic waves from an Hertzian dipole are plane polarized.



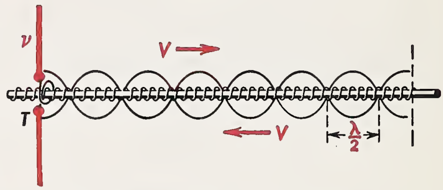
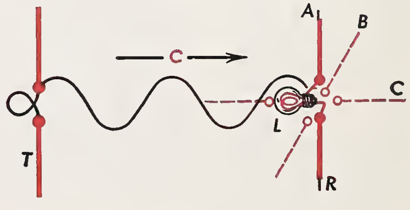


Fig. C. Standing waves on a wave guide.

Part 1. The first transmitter and receiver employs Hertzian dipole arms, each about 1 m long as shown in Fig. D. Rods, sliding in close-fitting metal tubes, enable the receiver dipole length to be adjusted to resonance.

The transmitter ***T*** is turned on and the oscillator tubes are given several minutes to warm up. With the receiver held parallel to the transmitter and about 3 m away, adjust the dipole arm lengths until the small lamp ***L*** glows its brightest. (*Note:* Do not bring the receiver too close to the transmitter as the light will glow too brightly and burn out.)

Fig. D. Arrangement for laboratory experiment on electromagnetic waves.



Now turn the receiver arms to position **B** and record the behavior of the light.

Turn the receiver arms to position **C** and again record the behavior of the light. These tests are concerned with the polarization of electromagnetic waves from the transmitter.

If the frequency of this transmitter is known, record this as part of your data.

(*Note:* With standing electromagnetic waves along conductors, current nodes coincide with voltage antinodes, and current antinodes coincide with voltage nodes.)

With the lamp filament ends connected directly to the adjacent dipole ends, the lamp burns brightest at a current antinode.

***Part* 2.** Set up the helical coil wave guide with the transmitter at one end and a meter stick clamped alongside, as shown in Fig. E.

Place the light-bulb detector **D** on the guide and move it along to detect the standing waves. The bulb in this case will light up brightly at the voltage antinodes and go out entirely at the nodes. Make a table of two columns as shown in Table 2 and record the antinode positions as read on the meter stick.

***Part* 3.** The second transmitter consists of a small Hertzian dipole about 6 cm to 7 cm long, mounted at the focal plane of a parabolic metal reflector about 20 cm in diameter. See Fig. F. The receiver has a similar dipole mounted in a receiver circuit box containing a milliammeter as a signal indicator.

Fig. E. Arrangement for laboratory experiment on standing waves.

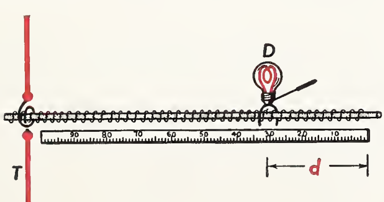


Fig. F. Microwave transmitter and receiver for laboratory experiments. (*Courtesy of the Central Scientific Co.*)

The transmitter is turned on and the oscillator tube permitted several minutes to warm up. Set the receiver about 6 ft away and direct it toward the transmitter. Turn up the input power of the transmitter until a reasonably good signal is indicated by the receiver milliammeter.

A plane sheet of metal about 40 cm by 40 cm should now be set up about 1 m in front of the transmitter as shown in Fig. G. Lay a meter stick on the table, with the zero end touching the reflector surface.

Move the receiver back and forth in the

Fig. G. Experimental arrangement for microwaves.

beam and locate the points of maximum response. Tabulate these positions as shown in Table 3.

Data. Assume the above procedures have been carried out and the data have been recorded as follows:

Part 1. Receiver in position ***A*** gives strong signal.

No signal in position ***B.***
No signal in position **C.**

Part 2. Transmitter frequency 78 Mc per second.

Table 2. Recorded Data

Voltage Antinode	Distance (cm)
1	4.2
2	12.0
3	19.8
4	27.9
5	36.1
6	43.9
7	52.0
8	59.8

Part 3.

Table 3. Recorded Data

Voltage Antinode	Distance (cm)
1	10.2
2	16.8
3	23.5
4	30.1
5	36.8
6	43.3
7	50.1

Calculations. Find the average distance between antinodes from your data in Part 2. Calculate the wave length and the velocity of the waves along the helical wave guide.

Find the average distance between antinodes from the data in Part 3. Calculate the wave length, and the frequency. Assume the velocity of light as given by Eq. (2).

Conclusions. What conclusions can you draw from the observations in Part 1? Briefly explain.

Does a voltage node or antinode form at the reflector in Part 3?

***Electronics* | Lesson 8**

GEIGER-MUELLER AND SCINTILLATION COUNTERS

This laboratory experiment is concerned with some of the characteristics of two widely used detectors of atomic radiation, Geiger counters and scintillation counters.

In order to make accurate counting rates with any radiation counter it is essential that one know the instrument's ***resolution time,*** or ***dead time.*** As the term implies, there is a certain time in the operation of any counter in which it is inactive or dead. When a single charged particle goes through a counter and is recorded, there follows a short period of time in which the device is

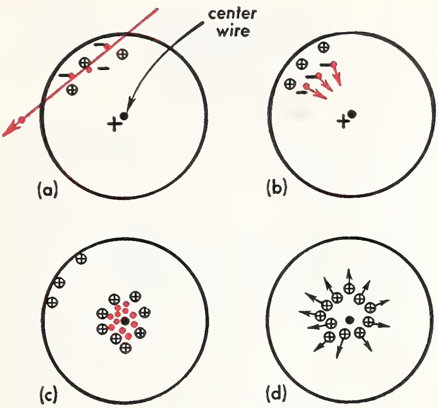


Fig. A. End on cross section of Geiger-Mueller tube showing electron and positive ion migration.

inactive. Should another particle traverse the tube during this period, it would not be detected.

Theory. The dead time for any counter depends upon a number of factors: the counter design, the gas used, the voltage applied, etc. The Geiger-Mueller tubes—as in Fig. A, Atomic Physics, Lesson 9—used in most Geiger counters have a dead time of a few milliseconds. When a charged particle passes through such a tube, several atoms become ionized by collision. In removing electrons from neutral atoms or molecules, positively charged atoms are left behind as shown in Fig. A(a).

As the electrons speed toward the central wire, as in diagram (b), they collide with other atoms, liberating more electrons as in diagram (c). The positive ions, being thousands of times heavier, move slowly toward the cylinder.

When the entire electron avalanche arrives at the wire and registers a voltage pulse, the many positive ions around the wire, as shown in (d), neutralize the strong electric field near the wire. Only when these ions reach the outer cylinder, to which they are attracted, does the tube become operative.

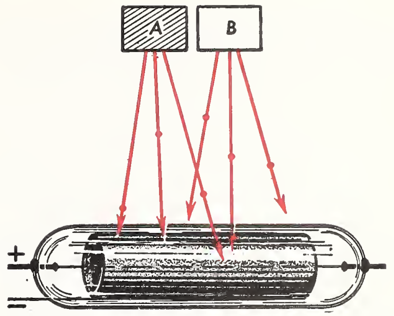


Fig. B. Radioactive sources in place for counting by a Geiger-Mueller tube.

If we denote the dead time of a counting device by T and the observed counting rate in counts per minute by N, the counter is insensitive for a time t given by

$$t = N\frac{T}{60}$$

where T is in minutes and t is the total dead time per second. The number of counts missed per minute will therefore be N times t.

$$\text{(counts missed per minute)} = N^2\frac{T}{60} \qquad (1)$$

Suppose we now place a radiation source A at some fixed distance from a counter tube as shown in Fig. B and determine the counts per minute N_A. Source A is then removed, and a similar source B is located in the position shown, the counts per minute N_B being determined. With source B in place, source A is brought back and placed exactly in its previous position, and the counts per minute N_{A+B} determined.

N_{A+B} will be somewhat less than $N_A + N_B$ because of the increased dead time. To obtain a value for T, the following formula can be used:

$$\boxed{T = \frac{(N_A + N_B - N_{A+B})\,60}{(N_{A+B})^2 - (N_A)^2 - (N_B)^2}} \qquad (2)$$

Having determined the value of T for any given counting device, one can then proceed

to measure the C/M of any source as N and make a correction for the dead time T. The correct C/M will then be given by

$$\boxed{N_c = N + N^2 \frac{T}{60}} \tag{3}$$

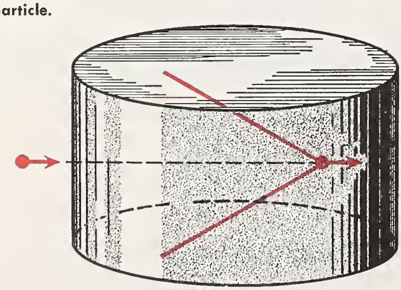
The principal advantages of scintillation counters over other detectors of nuclear radiation are first, they operate in air or in a vacuum; second, they deliver an electrical impulse which is roughly proportional to the energy lost by the traversing particle; and third, they can count at amazingly high speeds because of their extremely short dead time of 10^{-5} to 10^{-9} sec. When charged atomic particles pass through certain crystals, light characteristic of the substance is emitted. Such light is called ***fluorescent radiation.***

For many crystals this fluorescent light is blue or violet in color and therefore in a region of the spectrum to which phototubes are more sensitive. A scintillation counter is made by placing a block of fluorescent material—such as (a) zinc sulfide for α particles, (b) anthracene for β particles, or (c) thallium activated sodium iodide for γ rays—close to the photocathode of a photomultiplier tube.

If atomic particles enter a crystal with almost the speed of light, 3×10^8 m/sec, their speed in the crystal will be greater than the speed of light in the crystal.

The light waves produced by such high-speed particles are shown in Fig. C and are called ***Čerenkov radiation.*** Such a conically shaped wave is analogous to the shock wave from the nose of an airplane traveling with a speed greater than sound or to the V-shaped wave from the bow of a ship sailing faster than the speed of surface water waves.

Fig. C. Čerenkov radiation from a high-speed atomic particle.



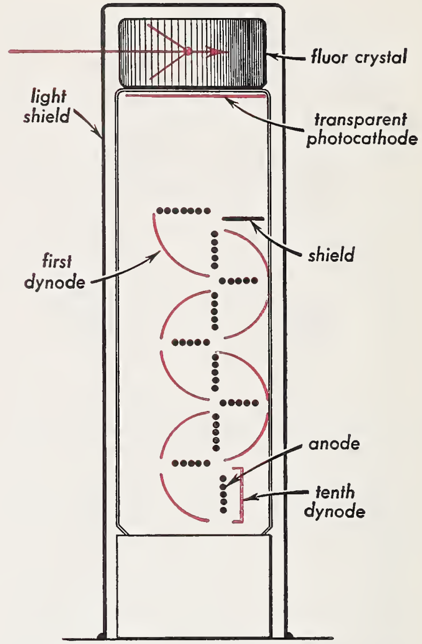


Fig. D. Cross section of a scintillation counter tube.

A typical scintillation counter tube is shown in Fig. D. The fluorescent block is mounted on the flat end of a special photomultiplier tube and then encased in a thin-walled, light-tight aluminum shield. When a particle traverses the fluor, the light ejects electrons from the photocathode, and the charge multiplication built up by the eight or ten dynodes make a sizeable voltage pulse that can be made to activate a counting-rate meter.

Apparatus. The Geiger counter to be used in this experiment is the same as the

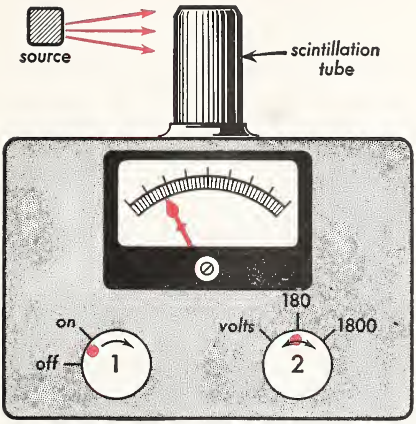


Fig. E. Scintillation counter arrangement for this experiment.

one used in Atomic Physics, Lesson 9. A scintillation counter of the simplest type, with a similar counting-rate meter attached, will be used for comparison measurements. Two comparable radioactive sources are also needed.

Scintillation counters, like the Geiger counter shown in Fig. E, Atomic Physics, Lesson 9, usually permit the measurement of wide ranges of counting rates by the turn of a dial. The diagram in Fig. E shows the detecting unit on top of a box containing the electrical counting circuits. With dial 2 in the 180 position, the counting-rate meter reading of ***M*** should be multiplied by 180, and in the 1800 position it should be multiplied by 1800.

Object. ***To compare and study the counting rate capabilities of Geiger-Mueller and scintillation counters.***

Procedure. ***Part 1 (Geiger Counter).*** Be sure dial 2 is in the "OFF" position before plugging the instrument cord into the wall socket .Turn dial 3 to the "VOLTS" position and dial 1 all the way clockwise (maximum volume).

Follow the procedure outlined in Part 1 of Atomic Physics, Lesson 9, p. 150, and set the tube voltage at the center of the "plateau."

Set dial 3 to the X 10 position and bring source ***A*** close enough to give a meter reading of about 750. Mark this position so that when the source is removed and later returned, it can be located in exactly the same position. Make a table of three columns with headings as shown in Table 1.

Remove all sources some distance from the counter and record the background counting rate of the meter. This residual counting is due to cosmic radiation that cannot be eliminated. Record this reading as shown in Table 1.

Bring up source ***A*** to its marked position and record the meter reading.

Remove source ***A*** and bring up source ***B*** to some position where it will give approximately the same meter reading as ***A***, and record.

With source ***B*** in position, bring up source ***A*** to its previously marked position and record the meter reading as shown in the last row of Table 1.

Part 2 (Scintillation Counter). Turn on the scintillation counter and set dial 2 in the 1800 position. With sources ***A*** and ***B*** far removed, record the cosmic ray background count in a table of three columns as shown in Table 2.

Bring up source ***A*** until the needle shows nearly a half-scale reading. Mark the source position and record the meter reading as shown in Table 2.

Remove source ***A*** and bring up source ***B*** to a position where it too will give nearly a half-scale reading. Record.

With source ***B*** in position, bring up source ***A*** to its previously marked position and record the meter reading.

Data. If the above steps have been properly carried out, the data will have been

recorded like that shown in Tables 1 and 2.

Table 1. Data for the Geiger Counter

Source	Meter Reading	Mult. Factor
zero	20	10
A	750	10
B	780	10
A + B	1240	10

Table 2. Data for the Scintillation Counter

Source	Meter Reading	Mult. Factor
zero	2.4	1800
A	9.2	1800
B	9.6	1800
A + B	16.2	1800

Calculations. ***Part 1.*** Make a table of three columns with headings as shown in Table 3.

Table 3. Calculated Results for the Geiger Counter

$\frac{C}{M}$	$\frac{C}{M}$ − Zero (N)	Corrected $\frac{C}{M}$ (N_c)
200	0	0
7500	7300	11,100

The first and second rows of values have been computed and will serve as a guide for the others.

The dead time T is calculated by Eq. (2) from the data in column 2. The corrected C/M values in column 3 are then found from this value of T and Eq. (3).

Part 2. Make another table of three columns with headings like those in Table 3 and fill in with your computations from the data on the scintillation counter in Table 2.

Conclusions. What can you say about the relative merits of the scintillation counter as against the Geiger counter? Briefly explain.

NUCLEAR PHYSICS

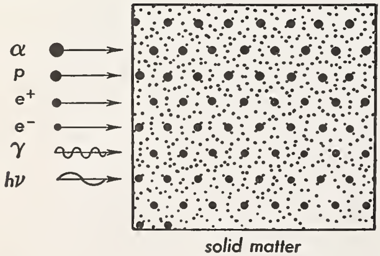
RADIATION MEASUREMENTS

Many aspects are involved in the measurement of nuclear radiation. There are not only a large number of different kinds of detecting and measuring instruments but also a considerable number of different kinds of charged and uncharged atomic particles involved in nuclear interactions.

A schematic diagram illustrating the passage of a few of the most common elementary particles through solid matter is shown in Fig. A. The atoms of the solid, represented by the regular array of black dots, are each composed of a nucleus surrounded by electrons. In passing through millions of such atoms each fast-moving particle, whether it is charged or not, will make numerous collisions with outer electrons and gradually come to a stop. Only on rare occasions is a single nucleus hit.

Theory. Suppose we have a beam of charged particles, like electrons, entering a solid body as shown in Fig. B. Because of the random collisions with electrons, particles are stopped within different distances of the front surface. At some depth d_1 the intensity I of the radiation will be reduced to $\frac{1}{2}I_o$.

Fig. A. In passing through solid matter high-energy radiation encounters millions of electrons and is gradually absorbed.



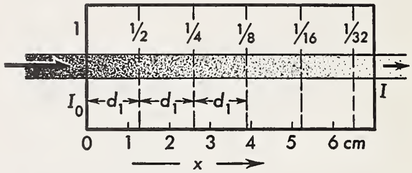


Fig. B. Schematic diagram of radiation absorption.

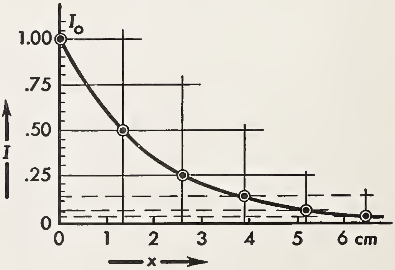
Imagine now that we divide this solid absorbing medium into layers, each of thickness d_1. The beam intensity $\frac{1}{2}I_o$ entering the second layer will be reduced to one-half of its initial value and emerge to enter the third layer with an intensity $\frac{1}{4}I_o$. Upon traversing the third layer, the entering beam $\frac{1}{4}I_o$ will be reduced one-half, or to $\frac{1}{8}I_o$, etc.

If we now plot a graph of the beam intensity I against the number of absorbing layers, or the depth $\mathbf{x}$, we obtain a curve as shown in Fig. C. This is known as an ***absorption curve***.

While the absorption curves for different kinds of rays and different absorbers are not alike, they are similar in that they all follow the same law. This law is in the form of an equation that represents the curve in Fig. C,

$$\log \frac{I}{I_o} = -\mu x \qquad (1)$$

Fig. C. Typical absorption curve.



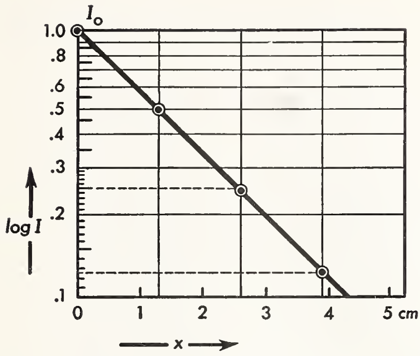


Fig. D. Semilog graph of radiation absorption.

where μ is a proportionality constant that depends on the nature of the rays and the absorbing medium, I_o is the initial intensity, and I is the intensity after traversing any thickness **x**.

To find the logarithm of any value of any number, like I/I_o, one can either look up the number in a table of logarithms or use the scale of a slide rule. The law is best illustrated by a graph as shown in Fig. D. The vertical scale is ruled by removing the slip stick from a slide rule and marking off the main lines and numbers. Note that the same points plotted in Fig. C now lie on a straight line. (Graph paper printed like this, with one scale a logarithmic scale, is called ***semilog graph paper.***)

The proportionality constant μ is often called the ***absorption coefficient*** and represents ***the fraction of the beam absorbed from the beam per centimeter path.*** Although μ varies from substance to substance, one finds experimentally that **x**, taken where I drops to any given fractional value of I_o and multiplied by the density of the absorber, is a constant for all materials.

$$\boxed{k = x_1\rho} \qquad (2)$$

Now suppose we have two kinds of rays present in a radiation beam, like β rays and γ rays from radium, and we detect them at various depths within an absorber. See Fig. E. The γ rays that have the greater penetrating power show less attenuation as they traverse the medium.

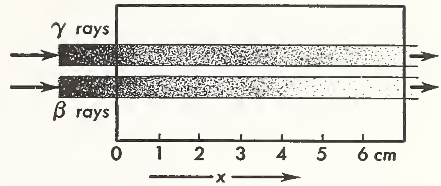


Fig. E. Schematic diagram shows absorption differences between β rays and γ rays.

If the rays are mixed and we plot a semilog graph of the total detected intensity I as it varies with depth, we obtain a curve as show in Fig. F. The upper left-hand straight section is due largely to the β rays.

Note that with 9 to 15 mm of absorber the direction of the curve changes. From approximately 15 on, the radiation is practically all composed of γ rays. The dotted lines indicate separate lines for the β rays and γ rays, and their sum is the solid line.

To find the value of the absorption constant k we find the value of x_1 where I drops to 1/10 the value of I_o, and multiply by the absorber density. To find the value of x_1 in Fig. F, the upper part of the curve is extended downward to where it crosses a value of $I = 3000$. This is 1/10 of I_o. The intersection at $x = 12.6$ mm, giving $x_1 = 1.26$ cm.

Since the density of the absorber used $\rho = .84$ gm/cm^3, the absorption constant is

$$k = 1.26 \times .84 = 1.06$$

Apparatus. The apparatus used in this experiment consists of a small radium source, two sets of absorbers, and a Geiger counter. A radium source gives out α, β, and γ rays, but the α rays are usually absorbed by the walls of any container. Consequently the radiation to be detected is a mixture of β rays and γ rays.

One set of 15 sheets of aluminum, about

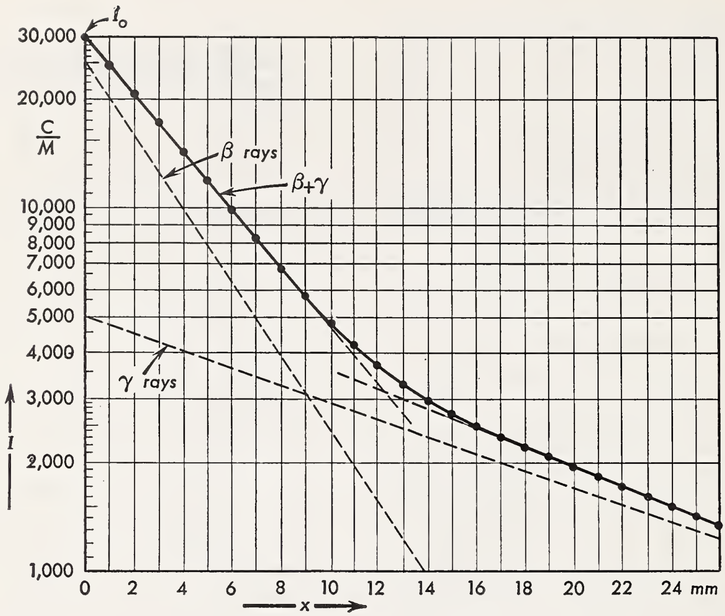


Fig. F. Semilog graph of radiation from a source containing β rays and γ rays.

10 cm square and 1 mm thick, and another set of 20 sheets of common cardboard 10 cm square and 1 mm thick, are to be used.

The Geiger counter is the same as the one used in Atomic Physics, Lesson 9, and Electronics, Lesson 8.

Object. ***To measure β ray and γ ray absorption by different substances.***

Procedure. Turn on the Geiger counter, following the instructions given in the previous lessons, and determine the ***plateau region***. Set the counter voltage at the center of the plateau and keep it set at this value for the entire experiment.

Set dial 3 to the X 10 position and bring up the ***Ra*** source to a point where the counting rate meter shows nearly a full-scale reading. Leave the source and Geiger-Mueller tube fixed in this position for the remainder of the experiment.

Make a table of four columns with headings as shown in Table 1. Record the initial meter reading after multiplying by 10.

Insert the first cardboard sheet between the ***Ra*** source and the Geiger-Mueller tube, and record the C/M.

Insert a second cardboard sheet between the two and again record the C/M.

Repeat this procedure, adding one absorber at a time until a total of 20 have been inserted, recording the C/M with each one. Allow time after the insertion of each absorber for the meter to reach its steady condition.

Remove all cardboard absorbers and carry out the same procedure with the aluminum absorbers. Record the C/M values in the two right-hand columns of Table 1.

Data. Assuming the above procedure has been properly carried out, the recorded

data will have the appearance of that shown in Table 1.

Table 1. Recorded Data

Cardboard		Aluminum	
N	C/M	N	C/M
0	12,900	0	12,900
1	10,800	1	6,900
2	9,300	2	3,800
3	8,000	3	2,400
4	7,000	4	2,000
5	6,000	5	1,800
6	5,200	6	1,700
7	4,500	7	1,650
8	3,750	8	1,600
9	3,300	9	1,550
10	2,850	10	1,500
11	2,500	11	1,450
12	2,250	12	1,400
13	2,100	13	1,350
14	2,000	14	1,300
15	1,900		
16	1,800		
17	1,700		
18	1,600		
19	1,500		
20	1,450		

cardboard size: 10 × 10 × 0.1 cm
aluminum size: 10 × 10 × 0.1 cm
mass of 10 cardboard abs = 702 gm
mass of 10 aluminum abs = 270.1

Results. Prepare a graph on semilog paper. Plot curves for both the cardboard and aluminum absorbers on the same graph.

If commercially ruled paper is not available, remove the slip stick from an 8- or 10-inch slide rule and use the **B** scale to lay off your vertical I scale. Starting with 1 at the bottom, mark all whole numbers up to 3 in the second scale. Label these marks 1000, 2000, 3000, . . . 30,000 C/M, as shown in Fig. F.

With a uniform centimeter ruling as a horizontal scale, label the centimeter marks 0, 2, 4, 6, . . . 20 to represent the number of absorbers or the thickness of total absorber in millimeters.

Weigh a set of 10 cardboard absorbers and a set of 10 aluminum absorbers, and record their mass in grams. Measure the size and thickness of one absorber and record in cm.

Calculations. Extend the upper straight-section of each curve downward and find the thickness x_1 that will reduce the beam intensity to $1/10\ I_o$.

From the weighings of absorber material, find the densities of cardboard and aluminum. These will be approximately 0.70 gm/cm^3 and 2.7 gm/cm^3, respectively.

Using these values of ρ and the values of x_1, calculate the absorption constant k.

Repeat these calculations for a beam intensity $I = 4000$ C/M.

Conclusions. Why is heavy shielding used around powerful sources of radiation? Does this shielding absorb all the radiation?

Appendix I

TRIGONOMETRIC FUNCTIONS (*Natural*)

Angle	Sine	Cosine	Tangent	Angle	Sine	Cosine	Tangent
0°	0.000	1.000	0.000				
1°	.018	1.000	.018	46°	.719	.695	1.036
2°	.035	0.999	.035	47°	.731	.682	1.072
3°	.052	.999	.052	48°	.743	.669	1.111
4°	.070	.998	.070	49°	.755	.656	1.150
5°	.087	.996	.088	50°	.766	.643	1.192
6°	.105	.995	.105	51°	.777	.629	1.235
7°	.122	.993	.123	52°	.788	.616	1.280
8°	.139	.990	.141	53°	.799	.602	1.327
9°	.156	.988	.158	54°	809	.588	1.376
10°	.174	.985	.176	55°	.819	.574	1.428
11°	.191	.982	.194	56°	.829	.559	1.483
12°	.208	.978	.213	57°	.839	.545	1.540
13°	.225	.974	.231	58°	.848	.530	1.600
14°	.242	.970	.249	59°	.857	.515	1.664
15°	.259	.966	.268	60°	.866	.500	1.732
16°	.276	.961	.287	61°	.875	.485	1.804
17°	.292	.956	.306	62°	.883	.470	1.881
18°	.309	.951	.325	63°	.891	.454	1.963
19°	.326	.946	.344	64°	.899	.438	2.050
20°	.342	.940	.364	65°	.906	.423	2.145
21°	.358	.934	.384	66°	.914	.407	2.246
22°	.375	.927	.404	67°	.921	.391	2.356
23°	.391	.921	.425	68°	.927	.375	2.475
24°	.407	.914	.445	69°	.934	.358	2.605
25°	.423	.906	.466	70°	.940	.342	2.747
26°	.438	.899	.488	71°	.946	.326	2.904
27°	.454	.891	.510	72°	.951	.309	3.078
28°	.470	.883	.532	73°	.956	.292	3.271
29°	.485	.875	.554	74°	.961	.276	3.487
30°	.500	.866	.577	75°	.966	.259	3.732
31°	.515	.857	.601	76°	.970	.242	4.011
32°	.530	.848	.625	77°	.974	.225	4.331
33°	.545	.839	.649	78°	.978	.208	4.705
34°	.559	.829	.675	79°	.982	.191	5.145
35°	.574	.819	.700	80°	.985	.174	5.671
36°	.588	.809	.727	81°	.988	.156	6.314
37°	.602	.799	.754	82°	.990	.139	7.115
38°	.616	.788	.781	83°	.993	.122	8.144
39°	.629	.777	.810	84°	.995	.105	9.514
40°	.643	.766	.839	85°	.996	.087	11.43
41°	.656	.755	.869	86°	.998	.070	14.30
42°	.669	.743	.900	87°	.999	.052	19.08
43°	.682	.731	.933	88°	.999	.035	28.64
44°	.695	.719	.966	89°	1.000	.018	57.29
45°	.707	.707	1.000	90°	1.000	.000	∞

Appendix II

VALUES OF THE GENERAL PHYSICAL CONSTANTS (AFTER DU MOND)

Planck's constant of action	$h = 6.6238 \times 10^{-34}$ joule sec
Electronic charge	$e = 1.6019 \times 10^{-19}$ coulombs
Electronic charge	$e = 4.8022 \times 10^{-10}$ e.s.u.
Specific electronic charge	$e/m = 1.7589 \times 10^{11}$ coulombs/kg
Specific proton charge	$e/M_p = 9.5795 \times 10^{7}$ coulombs/kg
Electronic mass	$m = 9.1072 \times 10^{-31}$ kg
Mass of atom of unit atomic weight	$M = 1.6600 \times 10^{-27}$ kg
Mass of proton	$M_p = 1.6722 \times 10^{-27}$ kg
Ratio mass proton to mass electron	$M_p/m = 1836.1$
Wien's displacement-law constant	$C = 0.28976$ cm deg.
Velocity of light	$c = 299{,}790$ km/sec
	$c^2 = 8.9874 \times 10^{10}$ km²/sec²

Appendix III

THE GREEK ALPHABET

Α	α	*Alpha*	Η	η	*Eta*	Ν	ν	*Nu*	Τ	τ	*Tau*
Β	β	*Beta*	Θ	θ	*Theta*	Ξ	ξ	*Xi*	Υ	υ	*Upsilon*
Γ	γ	*Gamma*	Ι	ι	*Iota*	Ο	ο	*Omicron*	Φ	φ	*Phi*
Δ	δ	*Delta*	Κ	κ	*Kappa*	Π	π	*Pi*	Χ	χ	*Chi*
Ε	ε	*Epsilon*	Λ	λ	*Lambda*	Ρ	ρ	*Rho*	Ψ	ψ	*Psi*
Ζ	ζ	*Zeta*	Μ	μ	*Mu*	Σ	σ	*Sigma*	Ω	ω	*Omega*

SAMPLE DATA SHEET FOR LABORATORY EXPERIMENTS

John E. Doe

Speed and Velocity
Lesson 2

Object. To make a study of a body moving with constant speed and another moving with constant velocity.

Equations Needed.

$$\boxed{v = \frac{s}{t}}$$

$$\text{circumference of a circle} = \pi d$$
$$\pi = 3.14$$
$$\text{distance traveled by train} = n\pi d$$

Apparatus. Toy automobile of sturdy metal construction, a geared-down motor with an attached drum, toy electric train, three-rail circular track, small train transformer for adjusting train speed, stop watch, meter stick.

Data.

Data for Car

Trial	Distance s (cm)	Time t (sec)
1	65.7	8.2
2	119.0	14.8
3	157.0	19.6

Data for Train

Trial	Number of Turns	Time t (sec)
1	4	21.4
2	5	26.7
3	6	32.1

track diameter d = 74.6 cm

Column Headings for Calculations and Results.

Results for Car

Trial	Distance s (cm)	Time t (sec)	Velocity v (cm/sec)

Results for Train

Trial	Number of Turns	Time t (sec)	Speed v (cm/sec)

Questions To Be Answered.

1. What is the average value of **v** for the car?
2. What is the average value of **v** for the train?
3. Which of the two measurements in this experiment, time or distance, has the greater probable error?

SAMPLE FINAL REPORT ON LABORATORY EXPERIMENTS

John E. Doe

Speed and Velocity
Lesson 2

Object. To make a study of a body moving with constant speed and another moving with constant velocity.

Theory.

Equations Used.

$$\boxed{v = \frac{s}{t}}$$

v = speed or velocity
s = distance traveled
t = time of travel

circumference of circle $= \pi d$

$\pi = 3.14 \qquad d = 74.6$ cm
distance traveled $s = n\pi d$

Apparatus and Procedure. In Part I a toy automobile is pulled across the table at constant velocity. This is accomplished by a string wrapped around a drum driven by a geared down electric motor. Two markers are set up as start and finish points, a meter stick is used to find the distance between them, and a stop watch is used to measure the time of travel.

In Part II a toy electric train is made to run around a circular track at constant speed. A single marker at the side of the track marks the start and finish points, and the stop watch is used to measure the time for any given number of turns around.

Data and Measurements.

Table 1. Data for Car

Trial	Distance s (cm)	Time t (sec)
1	65.7	8.2
2	119.0	14.8
3	157.0	19.6

Table 2. Data for Train

Trial	Number of Turns	Time t (sec)
1	4	21.4
2	5	26.7
3	6	32.1

track diameter $d = 74.6$ cm

Calculated Results.

Table 3. Results for Car

Trial	Distance s (cm)	Time t (sec)	Velocity v (cm/sec)
1	65.7	8.2	8.01
2	119.0	14.8	8.04
3	157.0	19.6	8.01

Table 4. Results for Train

Trial	Number of Turns	Time t (sec)	Distance s (cm)	Speed v (cm/sec)
1	4	21.4	936	43.7
2	5	26.7	1170	43.8
3	6	32.1	1404	43.7

track circumference = 234 cm

Conclusions.

1. The average velocity of the car is 8.02 cm/sec.
2. The average speed of the train is 43.7 cm/sec.
3. The distance between markers in Part I can be measured to within an accuracy of 1 mm. For trial 2, for example, this is 1 mm in 119.0 cm, or one part in 1190. This indicates a probable error of 0.1%.

The track diameter can be measured in several places and the average found to within an accuracy of 1 mm. For the track this is 1 mm in 74.6 cm, or one part in 746. This indicates a probable error of 0.13%.

Using a stop watch with tenth scale divisions, each time measurement, with a little practice, can be repeated to within one-tenth of a second. For the second time interval in Part I, this is 0.68% probable error.

The measurement of ***time*** therefore has the greater probable error in this experiment.

Index

Page references in Roman type indicate pages in the textbook, while those in italic type followed by the letter L indicate pages in the *Laboratory Exercises*.